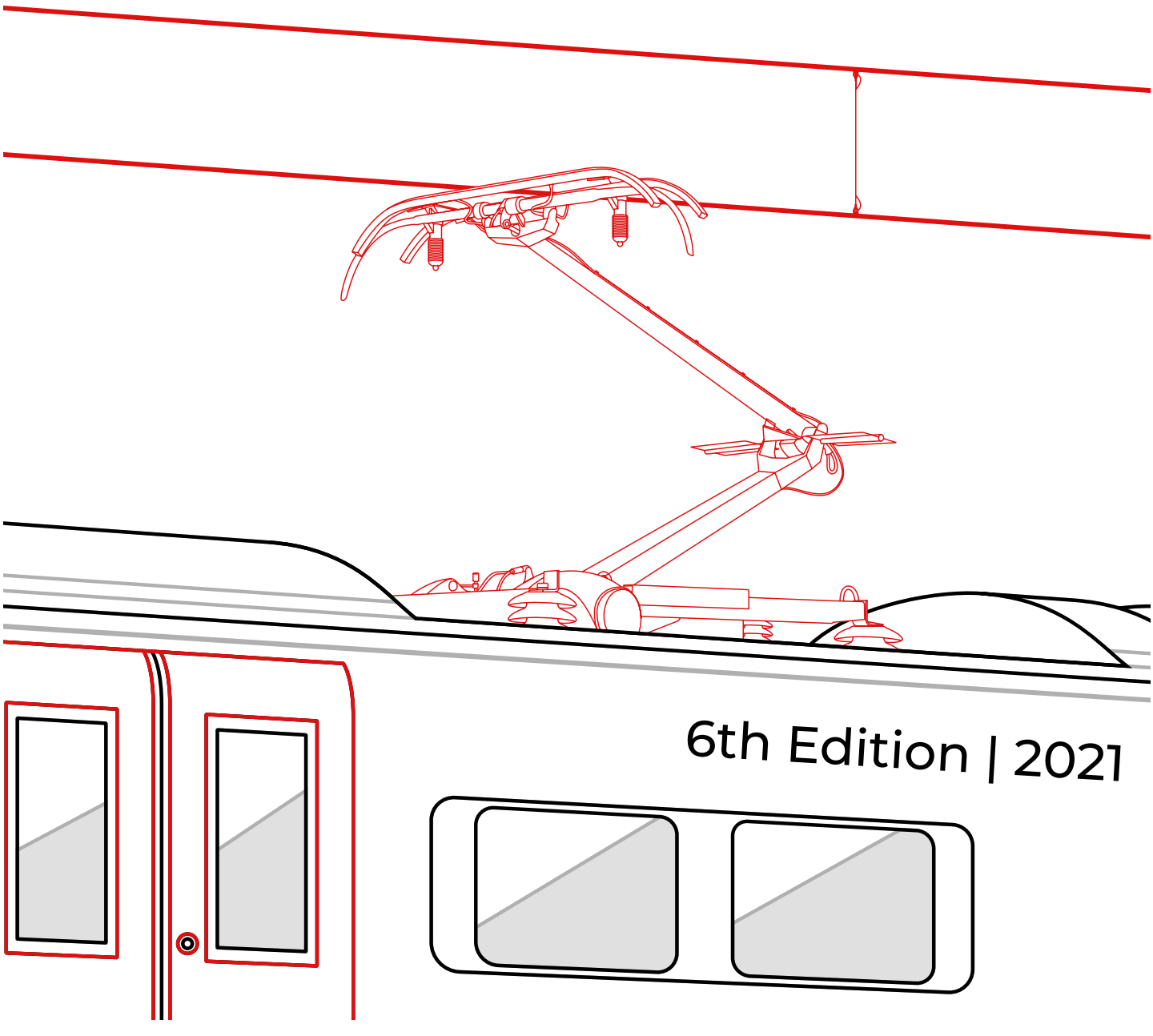
Overhead Line Electrification for Railways

Garry Keenor CEng FPWI MIET



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Overhead Line Electrification for Railways - 6th Edition

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Version Details

Edition	Date	Key Changes
6th	August 2021	Additional and expanded sections
5th	December 2018	Additional sections and diagrams, photo refresh
4th	November 2016	General update and refresh, GW and Series 1 practice included, general legislation and best practice update, focus on GLRT1210.
3rd	February 2012	General update, trolley bus section added
2nd	August 2008	AC & DC supply principles sections expanded, protection section expanded, materials section added, turnout wiring section added, spanwire portal added.
1st	October 2004	First issue

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1. Foreword

Since the earliest days of railways it has been obvious that it is senseless to haul the power plant around with the train. Isambard Kingdom Brunel clearly understood this. He realised that not carrying the weight of the steam engine gave significant advantage. Never one to pass by the opportunity to be in the vanguard of technical novelty, in 1840 he took on the building of the South Devon Railway over the Devon Banks. Seduced by the possibilities that technology used by the London and Croydon Railway offered, he advised the use of the "Atmospheric System". This used fixed steam engines to create a vacuum, and a 15 inch diameter pipe between the rails. A slot with a seal in the top of the pipe allowed a piston attached to a tow truck to be pushed along by atmospheric pressure.

Ignoring the reservations of his great locomotive Engineer, Daniel Gooch, the obvious railway operation limitation of a system only operable as a single line, and the folly of relying on greased leather as the only available way to seal the top of the tube around the mechanical connection between piston and truck, Brunel gambled the South Devon shareholders' capital. The decision drove that company to near bankruptcy, presented Gooch with the problem of building powerful enough locomotives to haul the trains and left us to this day with a line so aggressively graded and curved that train speeds remain severely restricted.

It is easy to dismiss the attempt to build a railway needing no self-powered locomotives as an act of hubris, but Brunel was in fact right; hauling the source of motive power is restrictive of train speed, causes more rapid degradation of the rails and track supports and is energy-inefficient. Mid-19th century technology was unable to realise Brunel's ambition, and it was not till 20 years after his death that the eventual solution began to emerge.

In 1879 Siemens and Halske demonstrated a technology destined to mature into electric traction. Siemens had produced an electric locomotive picking up electrical supply from fixed conductors at the side of the track.

Various systems for electric traction emerged; conductor rails on the ground and overhead lines were developed in various forms, some more successful than others. Whenever analysis has been undertaken through the last century, electric traction has always been found superior. But there is another theme which runs constantly through that history. Whilst the benefits of electrification of a railway are beyond debate, the capital cost of the fixed equipment and the service disruption involved in building the system leave no margin or fat in the cost benefit case. For that reason, in the UK electrification of the main line railways, which started in the late 19th Century, is still not complete.

The fifth edition of this book has been widely praised, accepted as required reading by practitioners in the UK (and across many other countries) and is an established reference guide for designers and engineers. This revised edition updates and adds to the wealth of detail. Practical examples are presented in such a clear and practical way that the book will be indispensable for beginners new to the discipline through to those with much longer experience.

Garry Keenor writes about and presents the complex and deeply technical aspects of OLE in a way which is engaging, and shares his widespread and deep knowledge making a great contribution to equipping future generations of Engineers and Designers to understand the intricacies of electric traction overhead line.

Since the first edition was published much has changed - changes to which the railway and indeed wider society must respond. Climate change due to human activity is no longer credibly questioned by anyone. The UK government has committed to a legally binding aim to bring our whole economy to net zero carbon by 2050. Transport is a significant contributor of atmospheric carbon and the only sector which is not reducing its burden; and so the railway has developed plans for traction decarbonisation. Battery and hydrogen powered trains will be part of that response, but neither technology can support high speed or heavy loads. The plan

is therefore to roll out overhead electrification across an additional 15,000 single track kilometres by 2050. All this must be done within the available resources of the UK economy and with competition for those resources from other sectors. It will be engineers who will lead the definition of economically affordable and practical answers to the many challenges that will bring.

With better background knowledge Engineers and Designers can produce better results. The challenge that all of us who dedicate our working lives to the traction electrification discipline is to keep the cost of electrification at a point where the economics work. The climate emergency means the case for finally providing a practical solution over the Devon Banks remains valid, and is in the traction decarbonisation plan. The continued relevance of railways in a post-carbon emissions world demands affordable solutions. For the specialist electrification Engineers and Designers who must rise to meet that challenge, this book will assist them along their path.

Peter Dearman
July 2021

2. Preface to the 4th Edition

The genesis of this book lies in a presentation I gave in 2003. A client on a major resignalling scheme asked for a lunchtime session on overhead line electrification, since most of their staff were unfamiliar with the system; and for the first time in my life my ego won out over my fear of public speaking and I accepted. The request for 30 minutes of material was soon forgotten in my new-found enthusiasm for powerpoint, as I proceeded to cram all my knowledge at that point into a file which grew to more than 70 slides.

The final product came in at over two hours, and I knew I was in trouble. Luckily my client was understanding and arranged to extend the session. I'm glad to say that my audience were also in forgiving mood, and most of them were still awake at the end. However, I had learned an important lesson: don't overstay your welcome on the stage.

So, having stripped back the talk for future sessions, I needed somewhere to put the more comprehensive material. I had always been struck by the paucity of accessible literature around the subject; when I was entering the industry at the tender age of 19, I was handed a slim booklet titled "Railway Electrification: 25kV a.c. Design on B.R."[1], and that was it. At the other end of the scale there is of course the standard text on the subject, "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance"[2]; but although fearsomely comprehensive (and expensive), even the most able engineer would not describe it as an easy read.

I therefore resolved to write something which would provide an approachable and reasonably comprehensive study of overhead contact systems, which would explain the *why* as well as the *what*, aimed at people with a basic mechanical and electrical knowledge who are new to the topic. In essence this is the book I would like to have been given when I joined British Rail as a graduate trainee. At the end of the book you will not be able to undertake all the tasks involved in OLE design, but I hope you will understand what needs to be done and why.

I am always nervous when an experienced colleague asks for a copy of the book, perhaps for one of their trainees. I do not pretend that everything is covered, and the book is inevitably biased towards my experience, which is predominantly 25kV AC systems in the UK. It is also exhibits a bias towards the mechanical side, with the electrical sections being less comprehensive. Additionally, this year's best practice can quickly become last year's unwise experiment, and so it is necessary to refresh the book from time to time.

3. Preface to the 5th Edition

The 4th edition was the first to be placed in the public domain, and I was naturally keen to get it published after months of preparation. A number of additional topics warranted inclusion, but some items weren't ready in time for publication - like so many engineers I have a troubled relationship with deadlines. The 5th edition includes these new sections and is (I think) the first complete version - in terms of topics at least.

4. Preface to the 6th Edition

When I wrote the words above for the 5th edition, I genuinely believed them. Alas, it is now clear they were pure hubris; in a system as complex as a railway there is always more that can be written, and further topics to

[1] Booklet is available online at www.railwaysarchive.co.uk/docsummary.php?docID=2.

[2] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag.

cover. Never again will make the mistake of claiming that the book is complete!

This edition contains several new sections that are beyond my own competence, and so I have leaned very heavily on both the written work of experts in their fields, and the kind assistance of several of those experts in checking my drafts.

New sections are as follows:

- Section 7.6 - alternative traction options;
- Section 10.2.2 - supply transformers;
- Section 10.2.4 - isolating transformers;
- Section 10.7.5 - rationalised auto transformer system protection;
- Section 10.2.8 - LV DC supply equipment in substations;
- Section 10.7.6 - power interlocking;
- Section 10.8.1 voltage controlled clearances;
- Section 11.19 - vehicle incursion, wildlife, vandalism and icing mitigations;
- Section 14 - trolley systems;
- Section 15.1 - 50kV OLE;
- Section 15.4 - inclined OLE;
- Section 15.7 - offset OLE;
- Section 15.6 - roundhouse OLE;
- Section 15.8 - electric-steam traction;
- Section 16.3.1 - bridge fixings;
- Sections 16.4 and 16.5 - OLE in modern and historic tunnels;
- Section 16.9.1 - signal supply points;
- Section 16.12 - overhead power lines;
- Section 17 - the planning phase;
- Section 18.1 - surveying;
- Section 19 - the construction phase;
- Section 19.2.2 - training spans;
- Section 20.5.1 - tether testing;
- Section 20.8 - entry into service;
- Section 20.9 - As Built drawings.

Updated sections are as follows:

- Section 7.3 - advantages of OLE;
- Section 10.1.3 - AC supply principles;
- Section 10.7 - protection, monitoring and control;
- Section 11.5 - turnouts;
- Section 16.8 - telecoms interfaces;
- Section 18 - the design phase.

New or amended sections are shown with a change bar (as right).

This edition also included a large number of new and improved images and diagrams. It also affords

the opportunity to correct several errors pointed out by readers of the 5th edition[3]. However new material means new potential for errors, so as always, corrections or clarifications are gratefully received at garry.keenor@gmail.com, or via twitter where I am @25kV.

The positive reception to the 4th and 5th editions has been overwhelming, and it is always nice to see a copy on someone's desk in an office, or in the background on a video call. I hope you will find this edition just as useful.

5. Acknowledgements

The production of this book is far from a solo effort, and for the 6th edition I relied even more on experts in fields adjacent to mine than for previous ones. I am incredibly grateful to all the individuals who have been so generous with their valuable time, expertise and encouragement.

The following people have provided specific input:

Zoe Armitage helped me understand geotechnical survey practice; Brian Armstrong helped with earthing and bonding; Graeme Beale provided help with side wear; Louise Benwell provided programme management expertise; Matt Bowey provided numerous corrections and clarifications; Ron Broomfield kindly donated his copy of Dover to me and opened a window into past design practice; Michael Y K Chung provided input on power modelling; Constantin Ciobanu helped with UK turnout geometry; Rob Daffern and Ankur Saxena assisted with OLE in tunnels; Bryce Denboer provided useful corrections on aspects of electrical equipment; Gareth Dennis helped with survey accuracies; David England helped with OLE materials; John Ewing provided photos of inclined OLE; Andy Gardner assisted with various sections; Peter Harris provided his invaluable expertise for the tunnel section; Paul Hooper helped with the electrical and planning sections; Ashley Jordan helped with protection systems; Stephen Lock helped with power & distribution advice and drawings; Adam McCreadie pointed me towards the current rules on mast rake; Allen McDonald helped with feeding and protection diagrams; Ed Mellor helped with structure loadings and foundation design; Robin Morel gave me guidance on current coasting practice; Laura Reardon provided hazard management expertise; David Shirres updated the picture on the tricky moving feast that is carbon emissions; Sanchay Singhal helped with ancillary conductors and isolators; Simon Skinner, Tim Young, Greg Salisbury, Tom Walker, Sam Hinks, Tim Ellis and Kenny Reith helped me to understand current construction practices; Bradley Wannell, Kara Jin, and Jamie Barratt kindly allowed the use of my survey photo; Anne Watters helped with the planning, design and construction sections; Dr Roger White helped with the dual voltage section, and along with Allen McDonald rescued my incorrect AT feeding description and diagram; Chris Wilson helped with traction power and P&D planning, design and construction, and made sense of my hopelessly confused transformer ratings numbers; and Martin Wright and Bernie Geiger offered good advice and guidance on trolley systems.

I've tried to keep good records as I've gone along, but if you helped and I missed you out, please accept my apologies and thank you!

Various colleagues and online friends have kindly given permission to use their images - a full list of credits is contained in the Table of Figures. Particular thanks are due to Morris Line Engineering for permission to use their isolator images, Pace International and Rebosio for permission to use their tunnel arm render, Barrow Hill Roundhouse Museum for providing access to their cross-arm pantograph, and SPL Powerlines UK for

[3] The complete errata list for the current version as well as all previous versions is available online at www.ocs4rail.com/errors.

assistance with the construction section and use of their images.

Peter Dearman did me the huge honour of writing an excellent foreword - without doubt the only time that my name will appear on the same page as Brunel's; and for that I am very flattered and grateful.

Arturs Dobrecovs did a fantastic job on the cover artwork - it's not often I get to be the client, and they were a joy to work with. If you need rail-related graphic design, look them up.

The responsibility for any errors remains (as always) with me and me alone, but there would be far more of them without the generosity of colleagues in agreeing to check the new material. In addition to all the people mentioned above who checked various sections, Simon Warren kindly repeated his role as overall proof-reader for this edition, and as always was remarkable unflustered when the 350 page draft landed on his (home) desk.

A number of people deserve special thanks for their patience and good career advice - without them I would not be in a position to write the book in the first place. They are: Erik Bates, Graeme Brindle, Alan Clegg, Peter Dearman, Paul Hooper, David Humphrey, Russell Jackson, Shaun Leatherbarrow, Allen McDonald, Ian Moore, Rob Tidbury, Andy Ward, Anne Watters, Mick Whelan, Dr Roger White, the late Adrian White and the late David Ingram.

Finally I must thank the people in my life who put up with my nonsense, keep me sane during times when I was tempted to give up, helped me make the book more than just a download, and aren't afraid to tell me when I'm being a jerk. Thank you to my ever-supportive wife Claire, and my beautiful and talented daughter Chloe.

Garry Keenor
Wiltshire
2021

6. How to Use This Book

This book gives an introduction to overhead line electrification systems for railways, and covers all types of railway and Overhead Line Equipment; all developments are covered, together with examples of UK systems. It applies to all overhead power supply systems for tram systems, light and heavy rail, low speed and high speed.

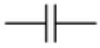
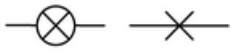
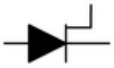
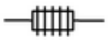
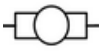
The book assumes a basic knowledge of maths and mechanical and electrical engineering concepts. All new terms are explained as the book goes along, and the explanation of a term is indicated by *italicised text*. Occasionally a term is unavoidably used earlier in the book, without explanation, in which case a cross-reference is provided, like this: (section 4). For those reading the document on-screen, these are clickable hyperlinks. Most images are high resolution and will benefit from zooming into the PDF.

Most PDF software has a search function triggered by typing [ctrl]+f – this is an easy way to find a reference from anywhere in the book.

Within the book the following terms are used:

Term	Definition
Beyond	Object A is beyond Object B when a train passes Object B before Object A
DMU	Diesel Multiple Unit
Distribution Network Operator	An operator of an electricity network whose voltage is no higher than 132kV
EMU	Electric Multiple Unit
Electricity Supply Industry	The whole of a supply industry, including Distribution Network Operators and National Grid Companies
High speed	Speeds above 200km/h
High Voltage (HV)	Voltages above 1000V
Heavy rail	Traditional railway systems; as opposed to light rail and tram systems
Low Voltage (LV)	Voltages up to 1000V
National Grid Company	An operator of an electricity network whose voltage is above 132kV
On approach to	Object A is on approach to Object B when a train passes Object A before Object B
Overbridge	A bridge over the railway
Road-Rail Vehicle	Any vehicle capable of being driven on a road and also driven along a railway
STK	Single Track Kilometre. One STK is equal to a kilometre of single track.
Substation	Generic term covering feeder stations, TSCs, TSLs, and AT sites, whether sectioning or intermediate
Underbridge	A bridge under the railway

Within the book the following symbols are used in circuit and mechanical diagrams:

Item	Symbol
AC Supply	
Auto Transformer	
Bonds (red, yellow)	
Capacitor	
Circuit Breaker (open, closed)	
Contactor	
Damper	
Earth	
Fault	
IGBT	
Insulator	
Inverter	
Isolator	
Load Break Switch (open, closed)	
Motor	
Neutral section	
Overlap	
Rectifier or DC substation	
Resistor	
Section Insulator	
Spring	

Item	Symbol
Surge Diverter	
Transformer (full, simplified)	
Winding or Inductor	
Wire Run (in running, out of running)	

Wires are referred to by their layup; that is, the number of strands and diameter of each strand. For instance, 19/3.25 wire comprises 19 strands, each 3.25mm in diameter. Elements and alloys are denoted by their periodic table symbol, or similar abbreviation, as follows:

Symbol	Metal
Ag	Silver
Al	Aluminium
Bz	Bronze
Cd	Cadmium
Cu	Copper
Mg	Magnesium
Ni	Nickel
Si	Silicon
Sn	Tin
Zn	Zinc
HD	Hard Drawn (generally applied to copper)

A footnote with the reference *ibid* means it is referring to the same document as the previous reference.

Parts of the book which are new or amended since the last version are shown with a change bar (as left).

Items which have been deleted from the last version are marked with a deletion square (as left).

7. Basics of OLE

7.1. What is OLE?

Overhead Line Equipment (OLE) is a system used to deliver continuous electrical energy to a stationary or moving train, by means of a sliding contact between on-roof current collection equipment and a fixed overhead supply conductor. It is also known in the UK as OHL or OHLE. In Europe and the US, it is known as *Overhead Contact System* (OCS), and in New Zealand, as *Overhead Wiring System* (OWS). The generic term for the system is *Overhead Contact Lines*.

This book will use OLE, as it is the preferred term in the UK.

7.2. Unique Features of OLE

Unlike other power transmission systems, OLE is required to transmit high power[4] to a stationary or moving load[5] at a distance of several miles. The contact wire is therefore a twin system – it functions as both power transmission mechanism and sliding contact with the train.

Figure 1: A shortened TGV train takes the world rail speed record on 3 April 2007

The key requirement for any OLE system is to provide continuous power to the train. For this to happen there must be continuous contact between OLE and the pantograph (section 11.1). Loss of contact leads to degradation of energy transfer and unwelcome damage to the contact wire and pantograph due to *electrical arcing*[6].

OLE is a very exposed system, being vulnerable to climate – especially wind, snow and ice; to wildlife – particularly birds; and also to pollution and vandalism. The mechanical and electrical forces imposed on OLE

[4] Up to 10MVA per train.

[5] The current railway speed record is held by a French TGV unit, which reached 574.8km/h on 3 April 2007 travelling under modified and super-tensioned (40kN) 31kV OLE. Video is available online at youtu.be/wfll-5h6Rg8.

[6] The localised heating of the contact wire during arcing is known to locally reduce wire hardness, creating the conditions for fatigue cracking and failure. This can reduce the life of the wire by up to 50%. "Laboratory Assessment of Arc Damage in Railway Overhead Contact Lines with a Case Study on Copper-Silver and Low Oxygen Content Copper", Sunar, Fletcher, Beagles; 2020; IEEE.

by repeated pantograph passages and heavy starting traction loads are significant; and these make unplanned events much more likely than in conventional transmission lines. OLE systems must therefore be capable of withstanding frequent *electrical fault* conditions without degradation of performance. The system tends to be constrained by other railway infrastructure, particularly in the UK where it has been retrofitted to railways built in the 19th century with small clearances above the train.

Figure 2: OLE and pantograph damage at 70km/h

Due to the continuous contact requirements, the contact wire position is critical to successful operation. There is no redundancy in this part of the system; a second contact wire is not a practical proposition, from either an engineering or financial standpoint. If the contact wire strays outside defined position limits, the pantograph will usually damage a significant length of the OLE before the train comes to a halt.

OLE is above all else a combined electrical and mechanical system, and the requirements of each must be balanced in the design.

7.3. Advantages of the System

Electrification is the most effective form of traction power for trains in terms of efficiency, performance, whole life cost and the climate emergency. These advantages are a result of the basic laws of physics[7]. A 2020 study concluded that "for areas of the [UK] network with significant freight flows or long-distance high-speed services, electrification is the only technology currently able to support [the decarbonisation of] these service types. Analysis suggests that electrification is also the best whole life cost solution for more intensively used areas of the network." [8]

[7] "Why Rail Electrification?", Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; section 5.1.

[8] "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 4.

7.3.1. Power Capacity

All self-powered trains must store their own traction energy, and need a power plant to convert that potential energy into kinetic energy to make them move. A self-powered vehicle's power and range is thus limited by the amount of energy it stores, and the capacity and efficiency of its power plant. The available space on a train limits the size of this plant. The fixed-capacity nature of all railways means that more space for energy storage and conversion equals less space for passengers and freight.

The above restrictions do not apply to electric trains, which can receive a large amount of energy whilst in motion; the amount of power is limited only by the specification of the electrification system and (during acceleration from rest) the available adhesion at the rail. Additionally electric trains are able to exceed their rated power for short durations in a way that is impossible for self-powered trains. This makes electric trains unique in their ability to provide high speed passenger and heavy freight transport.

7.3.2. Energy Efficiency

Electric trains are more efficient in their energy use since there is no energy conversion process other than that which takes place at the motor; the only losses are those from the generation, transmission and motor control processes. In addition, the regenerative braking capability of an electric train increases its efficiency further, recovering up to 20% of the energy consumed. This means a typical electric traction unit has between 182% and 237% of the power of a comparable diesel unit[9], while requiring only one third of the energy[10].

For urban transit, trams are seven times as efficient at using energy as an equivalently loaded diesel bus, due to the difference between rolling resistance of steel-wheel-on-steel-rail and rubber tyres on tarmac, improved drive efficiency and lower weight[11].

7.3.3. Carbon Emissions

Surface transport is the highest carbon emitting sector of the UK economy. While rail emissions are only a small fraction of that total, railway traction accounts for the majority of those emissions[12]. Electrification is the only form of traction power that can economically be used to decarbonise rail routes with significant traffic density, traffic frequency, train speed or journey distance[13]. Electric trains can also be powered by whatever power source generates electricity, both now and in the future. In this way they can take advantage of significant carbon reduction in electricity generation, and concentration of emissions at a single source enabling more efficient control[14] [15]. If their electricity is generated by renewables or nuclear power they also have net-zero

[9] "Why Rail Electrification?", Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; appendix 3.

[10] Generation-to-motor efficiency of electric trains is an estimated 80%, compared with batteries at around 65% and diesel or hydrogen at 25%. "T1145 - Options for Traction Energy Decarbonisation in Rail: Final Report"; RSSB, June 2019, p15.

[11] "The most energy efficient mode of Public Transport", Blaise Kelly; 4 July 2020; accessed 20 Dec 2020.

[12] "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 4.

[13] A 2020 study recommended that to achieve net zero carbon emissions, electrification was required to cover 84% of the UK network. Ibid.

[14] While carbon emissions are notoriously hard to accurately quantify, one study estimated electric train using the current UK generation mix produces only 40% of that of an equivalent diesel train, while the estimate using a projected low-carbon 2040 generation mix is less than 4%. Another estimated current emissions at 26.4% (passenger) and 14.1% (freight), with reductions to 11.3% and 6.1% in 2040. "T1145 - Options for Traction Energy Decarbonisation in Rail: Final Report"; June 2019; RSSB; piii; "Rail decarbonisation – Why Electrification is the Only Real Answer", David Shirres; 2019; Rail Engineer; p12.

[15] UK energy CO_2 emissions fell from 459 to 198 tonnes per GWh between 2005 and 2019, and are still falling; in Q1 2020 62.1% of energy came from low carbon sources, up from 50.2% in Q3 2016. "Selling Electrification", David Shirres; November 2020; Rail Engineer; "UK Energy Statistics, Q1 2020"; June 2020; Department for Business, Energy and Industrial Strategy; p1.

carbon emissions.

Electrification contributes further to emission reductions by driving *modal shift*. Road and air transport account for the bulk of transport emissions[16], and in the case of aviation and long-distance heavy goods vehicles, have no clear route to decarbonisation[17]. Moving some of these journeys to rail is an essential part of any net zero strategy, and electrification has been shown over decades to produce a *sparks effect*[18], with a jump in customer numbers as soon as a route is electrified.

All infrastructure change creates *embodied carbon*; that is, the carbon emissions which the construction process generates through the production of steel, concrete and other activities. This carbon debt must be taken into account when assessing any proposed decarbonisation measure. A 2019 study[19] concluded that electrification of a mile of two track railway would typically generate 313 tonnes of CO2e emissions, or 98 tonnes per *Single Track Kilometre* (STK). The UK network of 31091 STKs[20] currently produces 1.788m tonnes of diesel-generated CO2e per annum[21], giving a payback period for the embodied carbon from electrification construction of 2.8 years[22]. This demonstrates that electrification quickly becomes a positive decarbonisation measure.

7.3.4. Pollution Reduction

Combustion of diesel fuel, as currently happens in virtually all self-powered trains, produces sub-micron soot particulates (part of the $PM_{2.5}$ group of particulates[23]), as well as Nitrogen Oxides (NOx) and aldehydes. Studies are increasingly showing that these emissions are associated with a range of chronic illnesses, including asthma, heart attacks and strokes. Across the world air pollution is believed to be responsible for one in ten deaths[24], with vulnerable groups such as young children and the elderly at particular risk. Short-term exposure to NOx can cause inflammation of the airways and increase susceptibility to respiratory infections and allergens; and it exacerbates the symptoms of those who are already suffering from lung or heart conditions, shortening their lives[25]. Recent studies have found that enclosed railway stations have elevated $PM_{2.5}$ and NOx levels, and that even when brake dust and carbon strip (section 11.1) particulates are taken into account, electric trains produce less harmful pollutants than diesel trains[26]. Matters improve further when - as is already the case for most European countries - coal-fired electricity generation is all but phased out, eliminating the particulates created during coal combustion.

[16] Cars, vans and heavy goods vehicles produce 95% of all UK land transport carbon emissions. "Final UK greenhouse gas emissions national statistics: 1990-2017"; March 2019; Department for Business, Energy & Industrial Strategy; p19.

[17] "Net Zero Technical Report"; May 2019; Committee on Climate Change; p140, p169.

[18] "The Oxford Companion to British Railway History", Simmons, Biddle; 1999; Oxford University Press; p144.

[19] "Case study: Electrification Embodied Carbon Savings"; RSSB; 16 May 2019; accessed 13 February 2021. This figure does not include for enabling works such as bridge reconstruction, which can be expected to add a marginal amount to the CO2e figure.

[20] "Network Rail Annual Return 2020"; Network Rail; accessed 13 February 2021.

[21] "Table 6105 - Estimates of Passenger and Freight Energy Consumption and Carbon Dioxide Equivalent (CO2e) Emissions"; Office of Rail and Road; accessed 13 February 2021.

[22] This estimate assumes that every STK of electrification removes a pro-rata amount of diesel traffic from the UK network. This is likely to be a conservative assumption, since electrification schemes are typically targeted at routes with the heaviest diesel traffic.

[23] Particles with a mass median diameter of 2.5μm.

[24] "A Breath of Fresh Air: New Solutions to Reduce Transport Emissions"; January 2018; IMechE; p17.

[25] "Clean Air Strategy 2019"; 2019; Department for Environment Food and Rural Affairs; p16.

[26] "Air Quality in Enclosed Railway Stations", Thornes et al; University of Birmingham; 2016; sections 2 and 5.

7.3.5. Economic Advantages

Electric trains have a number of key economic advantages over self-powered trains, again as a result of basic physics. This means electrification usually has a good whole-life business case on all but lightly used or short-length lines, regardless of any imperative to decarbonise or reduce pollution. The economic advantages can be summarised as:

- Higher acceleration[27] and braking due to lower weight and ability to exceed rated power for short periods – meaning greater passenger capacity on routes with frequent stops and increased ability to recover from delays. Hydrogen and battery trains can only achieve this is by sacrificing range;
- Substantially higher freight haulage capability than with diesel locomotives, and attendant reduced freight journey times[28]. Reduced freight point-to-point times also reduces speed differentials between freight and passenger, contributing to increased passenger capacity;
- Lower rolling stock capital cost[29];
- Lower rolling stock operating cost, largely as a result of fuel and maintenance costs[30];
- Lower rolling stock maintenance costs[31] [32], due to the much smaller number of moving parts;
- Greater train reliability[33], for the same reasons as above;
- Smaller fleet requirements due to increased reliability, since fewer trains are out of service for maintenance;
- Lower track maintenance costs[34], driven by lower track forces from lighter power units;
- Reduced noise and vibration, improving passenger comfort levels.

Electrification also has economic benefits beyond the direct operational cost savings; the wider socio-economic benefits such as improved transport links should also be factored into the cost-benefit analysis for electrification schemes.

7.3.6. Advantages over 3rd and 4th Rail Electrification

Ground-mounted conductor rail systems form a significant minority of electrified railways worldwide, often as a result of the deployment of LV DC electrification prior to the development of train-borne rectification and control. However these systems are limited by current collection performance to about 160km/h, and are hazardous in unshielded top-contact form. Serious economic disadvantages arise from the need to provide more frequent and complex substations, as with DC OLE (section 10.5) - and so new conductor rail construction tends to be for extensions of existing systems rather than creation of new ones.

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[27] Typical rate of acceleration is 0.65m/s^2 for DMU, 1.0m/s2 for EMU. "Study on Further Electrification of Britain's Railway Network"; 2007; RSSB/Atkins; appendix D.

[28] "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 5.5.31.

[29] UK diesel vehicle capex is on average 12% higher than for electric vehicles. "Rail Value for Money Study – Rolling Stock Whole Life Costs – Final Report"; 2011; Arup; figs 2.10 and 2.11.

[30] Typical operational savings for a single passenger vehicle are between £2m and £3m, based on a 30 year life. Applied to 80% of the UK fleet, this would equate to between £¾bn and £1bn of annual savings. "Why Rail Electrification?", Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; appendix 3.

[31] DMU maintenance costs across Europe are typically 40% higher than for an EMU. "European Benchmarking of the Costs, Performance and Revenues of GB TOCs – Final Report"; 2012; Civity; p65.

[32] DMU maintenance costs worldwide are twice as high as EMUs. "Benchmarking identifies good practice in rolling stock maintenance"; 2006; Railway Gazette.

[33] A new UK EMU has an average miles per technical incident of 26906, against 10272 for a new DMU – more than 2½ times as reliable; a midlife UK EMU is still almost twice as reliable as the most reliable equivalent DMU. "Understanding the Rolling Stock Costs of TOCs in the UK"; January 2015; Steer Davies Gleave; section 4.51.

[34] Typical track wear and tear costs are 15% higher for diesel vehicles than for electric vehicles. "Network Route Utilisation Strategy - Electrification"; Network Rail; 2009; table 3.3.

7.4. Disadvantages of the System

Set against all of the advantages of OLE are a small number of disadvantages.

The disruption to existing services during construction of OLE on an existing railway corridor can be significant, and the lack of redundancy in the contact wire can cause significant constraints on the reliability of the railway if the system is not correctly designed, installed and maintained. Electrification of a route can lead to limitations on the use of diversionary routes at times of planned or unplanned disruption, although this is less of a constraint if the majority of the network is electrified.

The safety risks from high voltages require careful management, but should not be considered a disadvantage since the techniques and processes for doing so are well understood.

Figure 3: OLE damage causing major disruption. Bethnal Green, UK

However the dominant disadvantage of OLE is the high capital cost of installation. Because of this, and despite the whole-life economic advantages (section 7.3.5), it has historically been difficult to gain funding for new electrification schemes, especially in the UK. Railway finances adhere to the timeless dictum that money ultimately comes from only two sources: the taxpayer and the fare payer. It is usually national or local government that authorises electrification schemes, and they will only proceed if two conditions can be demonstrably met:

- That there is a reasonable return on their citizens' investment – in other words, that the capital outlay is paid for by reduced operational expenditure over a reasonable period of time;
- That the scheme can be built within the ceiling of available funding.

For this reason the focus of the planner, designer and installer must be to deliver a reliable system which minimises the whole life cost of the equipment (including maintenance and unplanned disruption costs), but not at the expense of an affordable capital outlay.

7.5. Efficiency and Rolling Programmes

The most effective way to minimise electrification capital cost is by means of a *rolling programme*; that is, a planned sequence of electrification schemes across a network, with a broadly constant volume of new electrification being delivered each year. This reduces costs in a number of ways:

- Continuity of work increases staff experience and skill over time, resulting in a highly-skilled workforce able to move from project to project;
- Processes, plant and materials can be refined over time, based on lessons learned from previous projects;
- Lower materials costs can be negotiated, based on economies of scale;
- Wastage of materials is avoided at the end of a project (section 19.2.4) since any surplus can be used on the next one;
- Competition for plant increases supply and lowers costs, as plant manufacturers and owners have greater confidence to invest in future work;
- Increased competition for design and installation contracts lowers costs, for the same reasons.

7.6. Alternative Traction Options

A number of energy storage technologies have been proposed as alternatives to electrification - in particular, battery and hydrogen. A 2020 study concluded that the overall feasibility of these technologies compared to electrification was as follows.

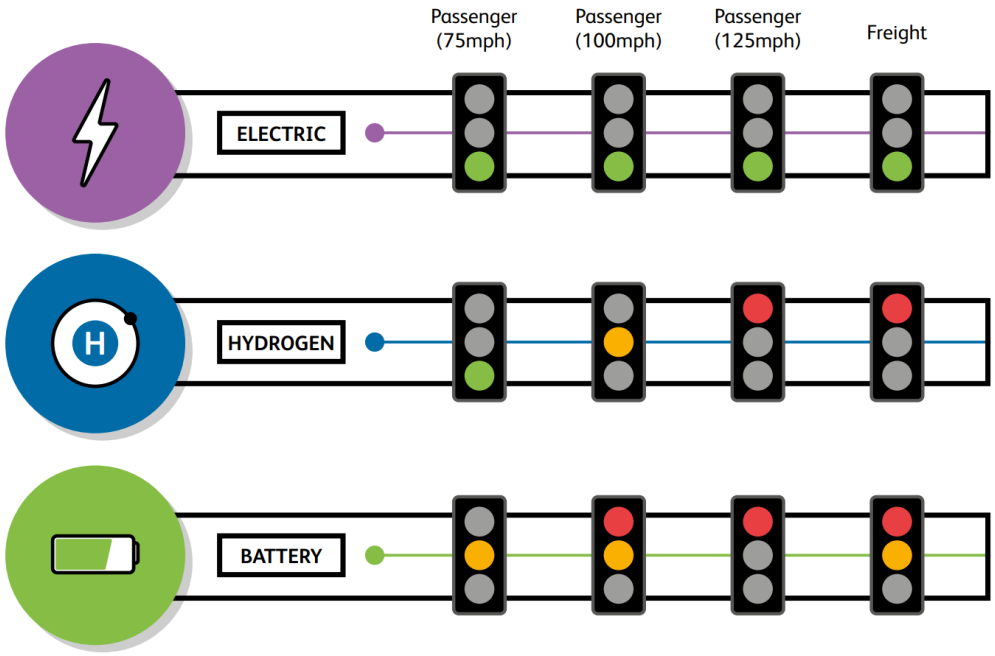


Figure 4: Technical abilities of non-diesel traction technologies[35]

These options are studied in more detail below.

7.6.1. Battery Only Traction

Battery trains suffer from some of the same constraints as other self-powered trains - they must store their energy on the train, and that storage consumes space which, on capacity-limited routes at least, can eat into the available space for passengers or freight. There are currently few battery trains in operation worldwide, so

[35] "Traction Decarbonisation Network Strategy - Interim Programme Business Case - Executive Summary"; Network Rail; July 2020; p4

it is difficult to assess real-world operational experience. The following section draws on the experience gained in the automotive Electric Vehicle (EV) sector to assess some of the challenges that will have to be overcome before battery trains can take their place in the traction hierarchy.

The current best-in-class Lithium Ion batteries have an energy density around 7% that of diesel fuel, and this limits both range and speed. Current battery trains have a 200kWh capacity, but reserves to maximise battery life mean the useful capacity is 130kWh. Energy consumption is 1.7-2.2 kW/km, giving a range of 60 to 80km and a maximum speed of 100km/h[36].

The energy density of batteries is however rising, chiefly fuelled by R&D in the automotive sector. There are few further gains to be made in Lithium Ion chemistry, and the new chemistries under development are expected to make incremental gains[37]. Even an optimistic estimate - doubling of energy density over the next 20 years - would mean an energy density of only one sixth that of diesel traction, and this will continue to be a significant limit on range and speed.

EVs typically consume only a small percentage of their battery capacity each day, before being charged again overnight[38], and the dominance of overnight trickle charging for EVs is the key to their long battery life[39]. This is not the case for rail vehicles, where it is central to their economic use that they are diagrammed for journeys totalling hundreds of miles every day, with only short stops at the end of each journey.

This means that, unlike EVs, frequent rapid charging - taking the battery from 20% to 80%[40] in under 20 minutes - is essential to the practical operation of battery rail vehicles. However rapid charging can cause significant battery heating, and this shortens battery life if used frequently[41]. For this reason it is expected that the batteries on a Battery Electric Multiple Unit (BEMU) would need to be replaced several times during the life of the train, increasing whole life costs.

Battery train manufacturers are now working on charging technology that could recharge the battery in seven minutes using charging currents of 1000A, with significant on-board battery cooling provided to maintain battery life. But with an electric vehicle's battery accounting for up to 20% of its total cost in 2020[42] and maybe 10% in 2035[43], the whole life economics of battery rail vehicles are not yet proven.

7.6.2. OLE-Battery Bi-Mode Traction

All of the above is predicated on a traction unit powered solely by batteries. In this configuration, the technology is only likely to be used on short, lightly-loaded routes where the electrification business case is harder to make. A promising alternative use for batteries is to provide supplemental power to a conventional electric traction

[36] "What Next for Vivarail?", Shirres; Oct 2020; Rail Engineer.

[37] Current estimates are that battery energy density will increase from 470Wh/litre today to 720Wh/litre in 2035, an increase of 53%. This compares with diesel fuel at 10.7kWh/litre. "Roadmap 2020: Electrical Energy Storage"; Advanced Propulsion Centre UK; 2020.

[38] The average UK car journey length in 2019 was 8.4 miles. "National Travel Survey"; 2019; Department for Transport.

[39] EV suppliers typically warrant that the battery will have at least 80% of its as-new range after eight years or 160,000km, regardless of duty cycle.

[40] It is key to the long life of current rechargeable battery chemistry that they are not frequently operated above or below these values.

[41] Charging a battery at a rate above 1C - that is, 1kW of charging rate for every 1kWh of capacity - increases heat stress which in turn increases battery ageing.

[42] Currently a BEMU battery costs £400,000 per train. "What Next for Vivarail?", Shirres; Oct 2020; Rail Engineer.

[43] Current estimates are that battery pack costs will fall from $125/kWh in 2020 to $63/kWh in 2035. "Roadmap 2020: Electrical Energy Storage"; Advanced Propulsion Centre UK; 2020.

unit, so providing a *last mile* capability to move short distances onto non-electrified branch lines or into freight yards, before returning to the electrified network for the remainder of the journey. In this configuration, both the range and rapid charging issues are potentially resolved; depending on the duty cycle, the battery can be trickle-charged from the OLE while on the electrified network.

7.6.3. Discontinuous Electrification

It is also tempting to view an OLE-battery train as a means of avoiding the more expensive parts of conventional electrification - particularly the wiring of low overbridges and tunnels (section 11.13.1). In recent years this concept has become known as *discontinuous electrification*. This is defined as two distinct arrangements at difficult overbridges:

1. Installation of permanently earthed sections of OLE (section 10.12.2), with neutral sections and power switching either side of the bridge;
2. Omission of OLE altogether, with OLE terminated either side of the bridge and pantograph lower/raise operations either side of the bridge.

Crucially, discontinuous electrification is positioned as a permanent arrangement at multiple locations on a route, aiming to avoid costly enabling works at these locations.

Since OLE is its own power transmission system (section 7.2) and power must be fed to the other side of the discontinuity, lineside feeder cables (section 10.2.9) must be provided to bridge the gap. Power mode changeover is typically triggered by lineside balises or *Radio Frequency Identification* (RFID) means, adding both lineside and rolling stock complexity. Recent experience with operation of diesel/electric bi-mode trains in the UK shows that there are significant operational and infrastructure constraints on the placement of changeover zones; this makes it very challenging to have multiple discontinuities on all but low-speed routes. Additionally, option 2 above offers only very marginal clearance advantages over a voltage controlled clearance arrangement (section 10.8.1), which provide virtually all of the same benefits without the disadvantage of an electrification gap.

For all of the reasons given in the previous section, the concept is unproven; few railways around the world operate with multiple discontinuities between electrified sections, and none of those that have discontinuities use batteries to bridge the gap. Furthermore this approach does not work for routes with freight traffic, since power demand for freight is much higher, precluding the use of batteries.

These arrangements effectively swap the high capital costs of enabling works at low bridges for increased capital and operational costs elsewhere. These costs, which are yet to be determined with any accuracy, include:

- Increased capital cost of rolling stock;
- Increased maintenance cost of rolling stock;
- Increased capital costs of lineside 25kV cables through bridges;
- Increased complexity and maintenance cost of OLE (for neutral sections on graded approaches to permanently earthed bridges);
- Additional cost and complexity of lineside power changeover mechanism.

Discontinuous electrification also erodes one of the basic economic tenets of a cost-effective national railway system - that is, the ability to repurpose electric rolling stock around a network built on common standards, as traffic patterns change and train fleets age. This *cascade* process, where a new fleet displaces a mid-life fleet to a secondary route, is at the core of railway fleet economics. A train designed for a discontinuous electrification route must inevitably be designed with that route in mind, in terms of battery duty cycle at least. This locks the fleet in to that route for its whole life (unless a costly rebuild is contemplated) and prohibits the use of any

other rolling stock.

Discontinuous electrification is due to be implemented on the Valley Lines in South Wales in the early 2020s, and this project will be closely watched to see if it can provide lessons for wider adoption of the concept.

7.6.4. Staged Electrification

A more appropriate use of non-continuous electrification is as a planned temporary arrangement as part of a rolling programme of electrification. For instance, a long route being electrified may need a track remodelling in one area; since it is not efficient to electrify in advance of this work, a non-electrified gap can be left for a period and then filled after the remodelling has taken place.

7.6.5. Hydrogen Traction

Recent years have seen a surge of interest in the use of hydrogen as a low-carbon alternative to diesel fuel. Hydrogen can be stored on-board a rail vehicle as a highly-compressed gas[44], and this this can be converted to electrical energy using an onboard *fuel cell*.

The energy density of hydrogen stored in this form is double that of a battery (section 7.6.1) but still only 14% of a diesel fuel tank. Current two-car hydrogen trains are able to store 188kg of hydrogen (6,300l per vehicle) and deliver 3200kWh to the motors once fuel cell and battery losses are taken into account[45]. This gives a range of 600-800km and a maximum speed of 140km/h; refuelling time is 15 minutes.

It should be noted that hydrogen trains still require a Lithium Ion battery - fuel cells work best when producing a broadly-constant output, and so the fuel cell charges the battery, which then drives the traction motors in the same way as a battery train. Current production fleets in Europe carry the hydrogen in roof-mounted fuel tanks, but the more restrictive UK loading gauge means that storage within a vehicle body[46] is likely to be needed, taking space that would otherwise provide additional seating. R&D on hydrogen is aiming to improve storage density by around 50%, and conversion efficiency by around 5%[47]. Regardless of the success of these efforts, the power capacity limitations rule hydrogen out for passenger trains above 160km/h and all freight.

An important difference between hydrogen and the diesel it seeks to replace is that hydrogen is not a naturally-occurring element; it must be synthesised, and should strictly be described as an *energy vector* rather than a fuel. Production currently takes place using steam reforming of hydrocarbons (usually methane) in large chemical plants, as it is almost entirely produced as part of a chemical process. The output is known as *brown hydrogen*, and the production process produces significant carbon emissions, making hydrogen produced in this way just as carbon-intensive as diesel. For hydrogen to be able to make a valid low-carbon case, it needs to be produced instead using electrolysis, with the electricity for the process produced using a renewable source such as wind, or excess electricity supply from a renewable source at times of low demand. This is known as *green hydrogen*.

The vector nature of hydrogen introduces another important consideration; that is, the requirements for hydrogen generation and distribution infrastructure. Centralised production would require the creation of a national grid for hydrogen storage and piping, as already exists in many countries for natural gas. With rail

[44] Current storage pressure is typically 35Mpa (5000psi).

[45] "Fuel Cell Coradia iLint On Test"; 12 Jan 2018; Railvolution; accessed 27 Dec 2020.

[46] This is expected to consume one third of one 20m vehicle on a four-car train. "Hydrogen Trains Coming Soon?", Shirres; Nov 2020; Rail Engineer; p33.

[47] Ibid.; p32.

only ever likely to be a small part of the hydrogen market, and all foreseeable national capacity being needed for the essential task of decarbonising home heating, this model is unlikely to deliver for rail. It is more feasible to adopt a local production model, with electrolysers, compressors and storage tanks provided at a depot location. These could be supplied from the local electricity grid, producing hydrogen at times of low energy demand (typically night-time) when electricity is cheaper, helping with local grid demand management at the same time. This is essential to avoid high energy costs, since the low efficiency of the production and compression processes means it takes around three times as much electricity to power a hydrogen train as it does an equivalent electric train[48]. A further step would be to generate renewable electricity locally, with a solar or wind installation close to the depot site.

With current hydrogen consumption rates a fleet of ten three-car trains doing 800km per day each would consume between 2000 and 3000kg of hydrogen. A 10MW electrolysis and storage facility would be needed to electrolyse and store two days fuel supply for this fleet, and this would occupy around 0.6 hectares[49]; the plant would require significant hazard control measures. The capital cost of this facility currently equates to around £1.7m per train, but this could fall by 50% as economies of scale take place[50]. An installation of two or three 2.5MW wind turbines on site could produce sufficient electricity to electrolyse this amount of hydrogen.

Capital costs for the rolling stock are likely to be higher than that of an electric equivalent, and the additional energy generation and hydrogen processing infrastructure must also be taken into account when assessing costs.

Hydrogen is without doubt the most promising of the alternative fuels for the extremities of a network, where lightly-loaded lines may not have the bulk electricity supplies needed for electrification. As with battery trains, the whole-life economic case is not yet proven[51], but hydrogen trains have been trialled in Europe and wider adoption is likely. However for the reasons above it cannot be considered as an alternative to electrification of core mainlines[52].

[48] "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 5.6.60.

[49] Based on calculations using data from Aberdeen hydrogen bus trial. "Data Sheet: Aberdeen, Scotland - Gaseous Hydrogen Fuelling Station for Buses"; 2017; BOC.

[50] "UK Renewable Hydrogen Hub: Techno-economic and Environmental Assessment"; April 2017; Innovate UK; p26-28.

[51] A 2020 study concluded that "The introduction of new battery and hydrogen rolling stock and the infrastructure they will require will be complex and will require new standards, operating procedures and products." "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 5.8.19.

[52] Ibid.; section 4.

8. Development of OLE systems

The following sections give an overview of the history of OLE development. For a more detailed list of UK builds, see Appendix A.

8.1. Electric Beginnings

The first OLE systems were used with passenger trams in the last years of the 19th century. These generally consisted of a simple single wire (trolley or tram) system, suspended from poles and buildings, and fed at a low voltage. This was preferred to the previous attempts with 3rd rail systems, which gave rise to both reliability and safety problems in congested on-street areas.

The first thirty years of the 20th century saw these principles extended to mainline systems as the advantages of OLE over 3rd rail became clear. As volt drop losses increased with distance, voltages were increased to compensate. At the same time, more sophisticated suspension systems were required to maintain good current collection at increasing linespeeds (section 11.2). At this time the national grid had not been developed, so railways often had their own power stations feeding at a variety of voltages and frequencies.

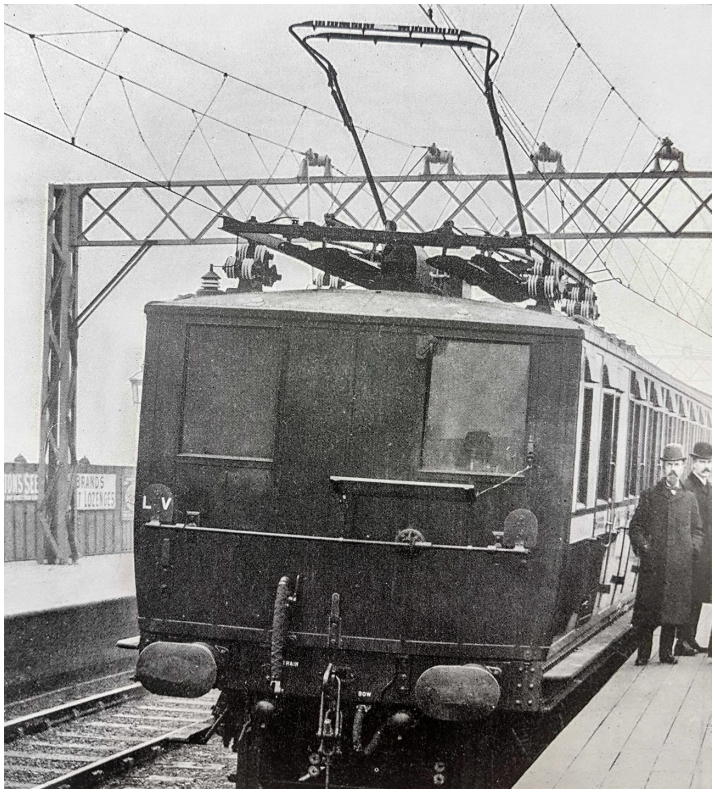


Figure 5: 6.7kV AC twin catenary simple OLE on the London, Brighton and South Coast Railway, circa 1910

Experimental AC schemes were implemented for the Lancaster to Heysham (1908) and London Victoria to London Bridge (1909) schemes[53], both at 6.7kV, 25Hz AC. AC motor technology was not mature at this time, necessitating complex train-borne rectification equipment, which gave reliability problems of its own. AC traction did not make any further headway in the UK until after World War Two.

In the north of England the Newport – Shildon line, which featured heavy coal trains running over steep gradients, was electrified with 1500V DC OLE in 1915.

[53] "Electric Railways, 1880 – 1990", Michael C Duffy; 2003; IEE; p74.

8.2. Mainline DC Growth

The barriers to using AC, coupled with the transmission limitations of DC current, meant OLE was only used for suburban and freight systems, where heavy electrical loads and short distances meant DC OLE made economic sense. In the UK, 1500V DC OLE was agreed in the 1930s as the national standard[54]. The Sheffield to Manchester and Wath route, which required very heavy coal trains to be hauled over the steep gradients of the Derbyshire peaks, was authorised for electrification in 1939, as was the Great Eastern Mainline (GEML) out of London Liverpool Street. However World War Two brought this, and all other electrification schemes in Europe, to an abrupt halt.

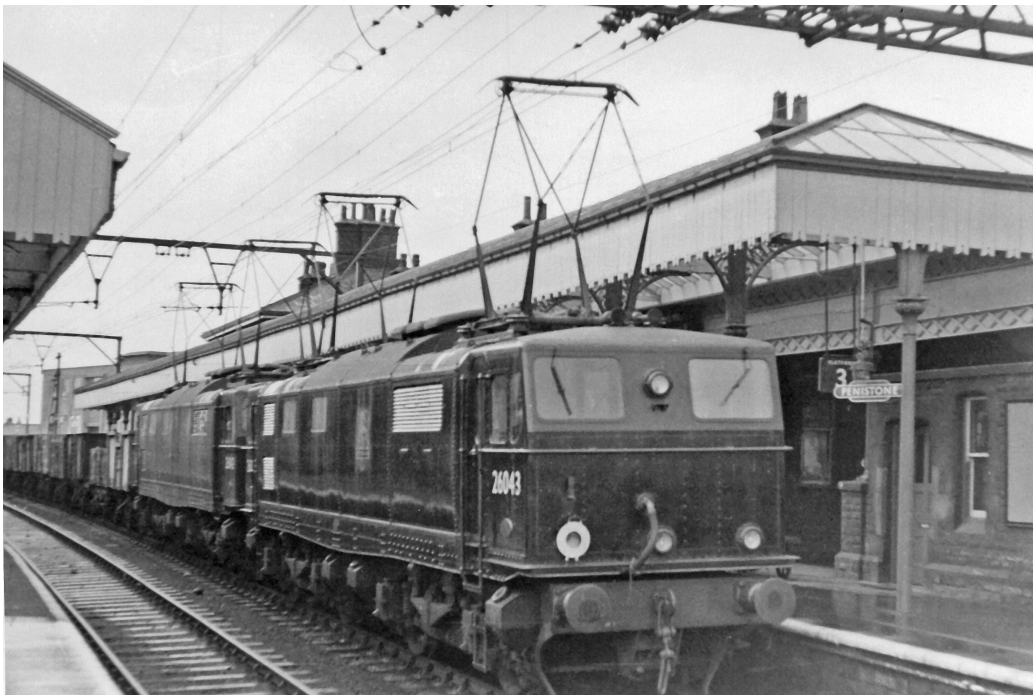


Figure 6: Electric freight with 1500V DC OLE. Penistone, UK

Both schemes recommenced after the war, but by now the railways' priority was rebuilding their battered infrastructure rather than funding new schemes. The Wath scheme was completed in 1952, but was a pyrrhic victory, since within 6 years the DC standard was obsolete. The line survived until 1981, by which time it was an isolated system. The GE lines fared better due to their essential commuting status, eventually being converted to 25kV AC.

The story of OLE in the UK during the first half of the 20th century is a faltering one, but the rest of Europe installed a large amount of 1500V DC in the pre- and post-war years, and much of this network still exists.

8.3. AC Developments

The 1950s saw increased interest in AC OLE, driven by the emergence from the electricity supply industry of reliable *industrial frequency* technologies. This meant that high voltage, long-distance AC transmission – and by inference, inter-city OLE – was now feasible. Experiments with 50Hz AC traction had first been made as early as 1940 in Germany[55]. Across Europe, as the 1950s progressed the 1500V DC standard was dropped in favour of 25kV at AC industrial frequency; in the UK this was approved as the standard for future schemes (using

[54] Ibid., p263.

[55] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p33.

50Hz AC) in 1956[56].

The Lancaster to Heysham route, which had pioneered HV AC OLE in 1908, was converted from 25Hz to 50Hz in 1951[57] to serve as a test bed for industrial frequency. These tests confirmed the choice as the right one. A further test scheme was installed between Colchester and Clacton in 1959. Various types of OLE were trialled, including simple and stitched equipment (section 11.2), but compound equipment was chosen as giving the best current collection at speed[58].

It was initially assumed that 25kV AC systems would require significant electrical clearances to existing infrastructure, and so 11" (275mm) was adopted as the standard air gap for bridges. In the UK this meant major reconstruction work, particularly for the many bridges in the vicinity of large stations, so for these areas a reduced voltage of 6.25kV was proposed, with 4" (100mm) clearances[59]. Trains would be dual-voltage and switch between them on the move as necessary, using neutral sections each side of the bridge.

Figure 7: 1500V DC on the GE; this was converted, first to 6.25kV AC and then 25kV. Gidea Park, UK

Experience on the Great Eastern (GE) lines out of Liverpool St, where the 1500V DC lines were converted to 6.25kV AC, showed that there was excessive caution in the standard clearances. Reduced clearances, and later special reduced clearances (section 10.8) were added, so that 25kV could be adopted throughout.

The West Coast Mainline (WCML) electrification was the first large scale 25kV scheme in the UK; it was planned to have 6.25kV sections, but in light of GE experience was implemented fully at 25kV[60]. The dual voltage locomotives which had been built for the route were modified as single voltage machines, and the 6.25kV areas were converted to 25kV.

[56] "Electric Railways, 1880 – 1990", Michael C Duffy; 2003; IEE; p321.

[57] Ibid.; p273.

[58] Paper; A D Suddards, T H Rosbotham, T B Bamford.

[59] "Electric Trains in Britain", B.K. Cooper; 1979; Ian Allan Ltd; p43.

[60] "Electric Railways, 1880 – 1990", Michael C Duffy; 2003; IEE; p322.

Figure 8: Mark 1 25kV AC on the WCML. Birmingham, UK

The first phase of the West Coast scheme was extremely successful in operational terms; it brought about a step change in service speed, and revived an image of high speed rail travel last seen in the 1930s. This was the first documented use of the term "sparks effect" (section 7.3.3).

However the railways were facing increasing pressure from an expanding motorways network, not to mention worsening finances, and when British Rail (BR) proposed a rolling programme of mainline electrification schemes, the Ministry of Transport made it clear that costs would have to come down.

BR responded with a wholesale overhaul in the design of OLE. The heavy, bespoke portal arrangements of the West Coast equipment were abandoned in favour of a new, lightweight, modularised, headspan-based metric system (the OLEMI – section 13.3). The first OLEMI system was known as Mark 3, and was further developed as Mark 3a; in this form it was used on the second phase of West Coast from Weaver Junction through to Glasgow in 1974.

8.4. High Speed Lines

Elsewhere in Europe, the possibilities for higher speed passenger trains using electric traction began to be explored. The French state railway SNCF began a series of experimental runs in the 1950s, culminating in a record-breaking run reaching 326km/h in March 1955. This used a modified 1500V DC system, with the line voltage increased to 1900V by means of mobile substations[61]. The record stood until 1981. The tests showed the obstacles to be overcome if speeds over 300km/h were to become the norm. Frictional heat caused the pantographs to collapse; track damage was so great that derailment was only narrowly avoided[62].

Figure 9: Track damage after the French 1955 high speed run

Japan was the first country to build an electrified mainline railway from scratch. The Tokyo - Osaka *Shinkansen* ('New Trunk Line') opened in 1964. This was segregated from existing lines, and used 25kV 60Hz AC OLE rather than the 1500V DC used elsewhere in Japan. The line had no level crossings and was designed for continuous high speed with linespeeds of up to 210km/h.

Figure 10: 0 series Shinkansen in Japan

France continued to develop their high speed system, and the *Ligne á Grande Vitesse* (LGV) concept was born. This would use dedicated high speed lines, high powered trains and a 50kV Auto Transformer system (section 10.4.3). Gradients were relatively steep, since the high power available meant that expensive embankment and cutting works would be minimised.

The first LGV between Paris and Lyon (TGV Sud-Est) opened in 1981. Since then, additional lines have been opened, and the concept has been exported to Germany (as the ICE), the UK (High Speed One) and worldwide.

[61] Ibid.; p389.

[62] Footage of the run is available online at youtu.be/1KRM1jAlpB0.

Figure 11: TGV Sud-Est in France

8.5. UK – APT and HST

In the mid-1960s BR began to investigate higher passenger speeds. Financial constraints ruled out LGV-style solutions, meaning any improvements would have to be delivered on existing routes. The newly-formed BR research division set themselves a target to achieve 250km/h speeds and a 40% increase through curves on the West Coast Mainline. The result was the *Advanced Passenger Train* (APT), which used active tilt to provide the required levels of passenger comfort through curves, as well as a host of other new technologies. Articulated bogies were used, where vehicle ends sat on a single bogie, thus improving ride quality. Two stage hydraulic/air brakes were used to improve braking performance. The pantograph was linked by chains to the bogie, thus countering the tilt of the train body.

Development of APT was prolonged – the gas turbine APT-E prototype ran until 1976, and the electric production model did not appear until 1978. While the project had obvious promise, many of the traditionalists in BR engineering were not convinced that the research division's gamble would pay off. The APT programme also ran into trouble with the unions, since the prototype did not have a second seat for double-staffing.

The traction & rolling stock division were convinced they could push diesel technology to provide sustained high speed running, and began to develop the *High Speed Train* (HST) concept. This pushed diesel traction design to the limit to produce a 200km/h fixed length diesel train, for use on the Great Western Mainline (GWML).

The train surpassed all expectations and set the standard for high speed passenger services for decades to come. The HST took the world speed record for a diesel train, reaching 232km/h on 12 June 1973, a record not surpassed until 2002. The project was so successful that the HST build was extended to provide higher speeds on the East Coast Mainline (ECML) and Midland Mainline (MML). This effectively stalled the mainline electrification program – in the case of ECML, by 10 years, and GWML and MML by 40 years.

On 20 December 1979 an electric APT took the UK speed record from HST, reaching 259km/h. However the complexity of the train proved to be its undoing. Major teething problems were encountered when the train entered service in 1981, and this was compounded by some ill-advised press runs leading to bad publicity, and the worst weather seen in years that winter. By 1984 BR were on the point of solving the technical problems,

but political backing for the project had evaporated and funding was stopped.

Figure 12: APT tilting on neutral section tests. Murthat, UK

APT was ultimately a failure of political will rather than technology. The lessons learned were taken by Italian train builders, who developed the *Pendolino* concept, successfully used throughout Europe – and now, ironically, sold back to the UK as for use on the West Coast Mainline.

8.6. Privatisation, Famine and Feast

Electrification proceeded in the UK through the 1980s, albeit on smaller schemes such as St Pancras – Bedford and Colchester – Ipswich. BR was finally given the go-ahead in the mid-1980s to continue electrifying the ECML north of Hitchin, and this was completed in 1991. However, budgetary constraints meant the OLE on this scheme had a weak power supply, and the OLE design was prone to failure.

Infill schemes continued in the 1990s, with Cambridge to King's Lynn, Carstairs to Edinburgh and London to Heathrow Airport all completed. A significant milestone was the opening of the Channel Tunnel, operating at 160km/h with OLE. However privatisation had broken the link between infrastructure capital cost and train maintenance saving which was vital to justify the initial cost of electrification schemes. The splitting of rolling stock procurement, rolling stock operation and infrastructure ownership led to a huge increase in diesel procurement, as no organisation would benefit from the whole life advantages of electric traction.

By the early years of the 21st century the only major schemes in progress were the West Coast upgrade, and the *Channel Tunnel Rail Link* (CTRL), which finally brought true high speed (300km/h) running to the UK. Section 1 of CTRL opened in 2003, and section 2 into London was opened in 2007. This line was subsequently renamed *High Speed One*. On 30 July 2003, a Eurostar test train took the UK rail speed record from the APT, reaching 334.7km/h (208mph) on section 1 of CTRL.

Figure 13: Class 374 Eurostar on High Speed One. Medway, UK

The middle part of the 2000s saw the beginnings of renewed interest in OLE in the UK, as a surge in oil prices, increasing environmental pressure, and new diesel emissions regulations all affected the economics of diesel traction. In 2010, with both the HST and the associated signalling systems approaching life-expiry, the UK government committed to a new programme of electrification on the GWML, as well as the Midland Mainline and routes in East London, the West Midlands and the North West. Meanwhile, the Scottish government authorised multiple schemes in the central belt. Altogether this committed the industry to deliver over 2,400 STKs of new electrification within a single five year Control Period.

Figure 14: A Hitachi IET forms the first electric train to run on the Reading-Didcot section of Great Western on 17 July 2016. Cholsey, UK

While many of the later schemes were delivered on time and within budget, most of the early ones fell victim to the inevitable problems that come with trying to deliver large volumes of a type of work not undertaken for

decades previously. The most high profile of these, the Great Western Electrification Programme (GWEP), ran heavily over programme and budget, resulting in cutbacks to the extent of the scheme, as well as cancellation of large parts of the Midland Mainline scheme in a bid to rebalance Network Rail's budget.

8.7. Decarbonisation and Renaissance

As the industry learned from the failures and began to deliver schemes on time and budget, the climate emergency was increasingly impinging on policy-makers' thinking. In 2019 Network Rail was asked to deliver a plan for making UK rail carbon-neutral by 2050. With diesel traction accounting for a large majority of carbon emissions and rail being the only form of transport with a proven route to carbon neutrality, this put electrification firmly back on the agenda. In 2020 Network Rail delivered the Traction Decarbonisation Network Strategy (TDNS) report[63], which recommended over 11,000STKs of new electrification over a 30 year period, taking the proportion of the UK network electrified from around 46% to over 80%[64].

At the time of writing it appears that politicians have begun to grasp the urgency of the issue and commit to a rolling programme of electrification; the Scottish government has embarked on a plan to fully decarbonise Scotland's railways, and the UK government has committed to "an ambitious, sustainable and cost-effective programme of electrification"[65] for England and Wales, based on the TDNS.

[63] "Traction Decarbonisation Network Strategy - Interim Business Case"; July 2020; Network Rail.

[64] As measured using STKs.

[65] "Decarbonising Transport - A Better, Greener Britain"; 14 July 2021; Department for Transport; part 2a.

9. Categories of OLE System

The parameters of an OLE system must be matched to the railway to which it is to be applied. OLE systems fall into one of five broad categories.

9.1. Tram Systems

Trams are *mass transit* systems, used to move large volumes of people over relatively short distances at relatively low speeds (up to 80km/h), usually in and out of urban centres. These systems feature *on-street running*, tight radius curves, steep gradients, short *headways* between trams and *line of sight* driving (i.e. no signalling except at highways interfaces). They are usually of post-war vintage.

Tram OLE system design is driven by the need to ensure the safety of the public, and by the many interfaces with buildings and highways. The systems are low voltage (usually 750V DC) and are often split into on-street and off-street equipments; the former being characterised by high contact wire, fixed termination tramway equipment (sections 11.2 and 11.3) and support from buildings, and the latter by a more conventional system with catenary and auto-tensioning. Support assemblies are very light, and double insulation (section 10.10.2) is used to prevent stray currents from entering buried services.

Figure 15: Typical street-running tram with building-suspended OLE. Birmingham, UK

9.2. Trolley Systems

Trolley buses also provide mass transit, and are used to provide low-pollution electrified public transport without the high cost and disruption of laying rails in city centres. The system consists of an *unguided trolley bus* controlled and steered by a driver in the same way as a conventional bus, but powered via trolley OLE (section 14) which is usually suspended from adjacent buildings.

Figure 16: Trolley bus system showing complex double pole insulation and tight radius curve. Lucerne, Switzerland

Uniquely for an OLE system, the lack of running rails means that traction current cannot return to the supply point using the rail. Therefore the OLE is a *double pole* system, with outward and return contact wires insulated from earth and each other. These provide both circuit legs, and a pair of trolley poles (section 14.1) on top of the trolley bus collect and return traction current. The double pole arrangement leads to additional insulation complexity wherever routes converge or diverge.

Trolley bus systems are popular in continental Europe and elsewhere, and share many common features with tram systems. In some cities such as Bern the two types of transport run on a common support system.

9.3. Light Rail Systems

Light rail systems are a step up from trams. They are also mass transit systems, situated in and around urban centres, but they do not feature on-street running, and share many of the characteristics of heavy rail, such as fixed signalling. Speeds are usually below 120km/h.

For these systems, supply voltages are higher (1.5kV DC or 25kV AC), and the OLE is often fixed termination, with simple catenary (section 11.2). Structures and assemblies are lightweight, and headspans (section 11.10.7) are often used. The Tyne & Wear Metro is an example of such a system.

Figure 17: Typical 1500V DC metro. South Hylton, UK

9.4. Mainline Systems

Mainline systems form the bulk of the OLE railway route mileage worldwide. These systems are mainstream traditional railways; speeds may be anywhere up to 200km/h, and traffic may be heavy and frequent, with a mix of passenger and freight. The railway may date from Victorian times, the OLE having been superimposed at a later date.

Standard supply voltages are 1.5kV or 3kV DC, and 15kV or 25kV industrial frequency AC (25kV being standard for all systems since the 1960s). OLE is either simple or compound auto tensioned (section 11.2 and 11.3); assemblies are heavier, and portal (section 11.10.6) or headspan (section 11.10.7) structures may be used. Fixed termination equipment is often used in sidings and terminal stations.

9.5. High Speed Systems

Mixing passenger services with slower moving freight at speeds above 200km/h is neither practical nor safe. For this reason, high speed systems are usually dedicated to passenger services; the high power available often means steep gradients are used, reducing construction costs. These lines are usually less than 40 years old, and built with large radius curves, generous OLE clearances (section 10.8) and no OLE gradients (section 11.13.1). Service speeds are typically 300km/h or 350km/h.

The standard supply voltage is 25kV industrial frequency AC, usually with a transmission voltage of 50kV and an Auto Transformer system (section 10.4.3). Good current collection becomes paramount; OLE is either sagged simple, stitched simple or compound (section 11.2). Assemblies are lightweight, and structures are a mix of portals and cantilevers (section 11.10).

Figure 18: Typical high speed railway - Class 395 on High Speed One. Medway, UK

10. Electrical Principles

10.1. Supply Voltages and Currents

10.1.1. Transmission and Supply Voltages

Transmission Voltage is the voltage at which energy is transmitted to the train's location. *Supply Voltage* is the voltage at which the train is supplied with energy.

For the majority of systems, the transmission and supply voltages are the same. However, some high speed lines use a higher transmission voltage to avoid excessive volt drop losses and thus provide more power at the train.

A variety of supply voltages are used around the world, due to a combination of historical and operational factors. 750V DC is standard for tram systems, and is chosen to minimise safety issues in public areas. 25kV AC, at a frequency equal to the country's industrial supply frequency (50Hz in the UK), is used for the majority of new mainline and all new high-speed builds. Most countries (with the notable exception of the UK) have a legacy network of 1500V DC OLE, and Northern Europe has a sizeable 15kV AC 16.7Hz network.

It should be noted that the supply voltage is not a single constant value, since volt drop losses, magnitude of load in section and other factors affect the supply voltage at the train. For instance, below are the allowable voltages for UK 25kV AC systems [66] .

System Voltage	Description
12.5 kV	Minimum voltage at which a train should continue to operate for not more than two minutes without being damaged (for existing electrified routes only).
14 kV	Minimum voltage at which a train should continue to operate for not more than ten minutes without being damaged (for existing electrified routes only).
17.5 kV	Minimum voltage at which a train should continue to operate for not more than two minutes without being damaged (for new electrification schemes).
19 kV	Minimum at which train equipment should operate continuously
22 kV	Mean useful voltage at the pantograph for routes with speeds $\leq$ 200km/h
22.5 kV	Mean useful voltage at the pantograph for routes with speeds $>$ 200km/h
25 kV	Nominal system voltage
27.5 kV	Maximum voltage at which train equipment should operate continuously
29 kV	Maximum voltage at which a train should continue to operate for not more than five minutes without being damaged

Each system will have a line voltage performance specification in this way, and the OLE system design is tailored to meet this.

[66] GLRT1210 "AC Energy Subsystem and Interfaces to Rolling Stock"; Issue 2, December 2019; RSSB; appendix D, table D.1.

10.1.2. Supply Current

The supply current is dependent upon the train power characteristic and the number of trains in section at any one time. For Low Voltage (LV) DC systems, the supply current is relatively high.

Train Type	Typical Train Starting Current Draw
750V DC three car tram	~1100A
750V DC train	~3000A
1500V DC train	~1500A

For AC systems, the higher voltage available means lower supply currents.

Train Type	Typical Train Starting Current Draw
25kV AC passenger train	~200A
25kV double headed freight train	~500A

Of paramount importance is the *maximum fault current* – the highest current which will flow under fault conditions. The entire OLE system must be designed to withstand many such faults over the lifetime of the equipment, without degradation of the components. For UK classic 25kV systems (section 10.4.4), the maximum fault current is 6kA. For new auto transformer systems (section 10.4.3), an increased level of 12kA or 15kA is generally specified.

Figure 19: Ends of contact wire which has parted during an undetected 25kV fault

10.1.3. AC Supply Principles

AC systems do not require rectification equipment, and AC electrical arcs are easier to extinguish when they cross zero volts, which means they can use higher voltages than DC. The resultant percentage volt drop is much lower, and so feeder stations can be further apart than for DC systems – for a standard 25kV feeding system, feeder stations are 40 to 60km apart. This eliminates the requirement for a separate HV feeding network.

Supplies have traditionally been obtained at each feeder station from the 132kV *Distribution Network Operator* (DNO). 25kV is obtained through 132/25kV transformers supplied by the DNO. These are often duplicated to give a backup supply or *redundancy*. These transformers are usually procured by the railway but owned and maintained by the DNO. They may be sited at a DNO compound alongside the railway feeder station, or sited

at a remote DNO site with 25kV cabling between the two.

New UK installations are now taking their supplies from the 400kV *National Grid Company* (NGC) system, which can withstand a much greater load imbalance and therefore provide much greater power capacity (section 10.4.3). By the mid-2020s it is possible that mainline rail will be the biggest single consumer of electricity in the UK.

The single phase supply taken from the three phase system at each feeder station creates an unbalanced load (or *phase imbalance*) on the *Electricity Supply Industry* (ESI) system. The ESI imposes contractually agreed limits on its customers on the total imbalance, and the railway is usually the biggest single contributor to this imbalance. For example, the ESI UK limits are 1.5% on the grid or DNO[67]; and 0.5% maximum contribution by the railway. This is one of the key reasons for moving to a 400kV-derived supply for high power railways.

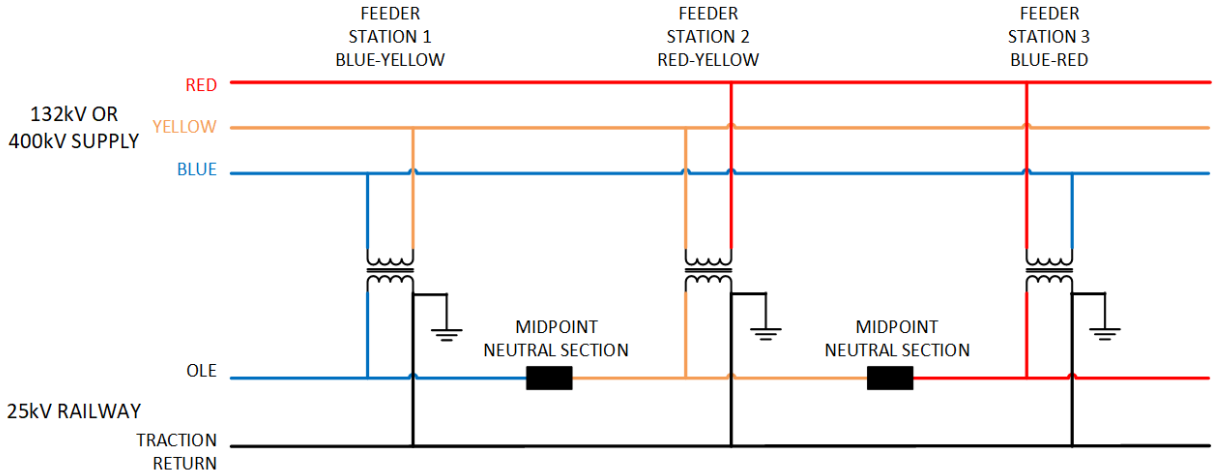


Figure 20: Principles of feeding a single phase railway from a three phase ESI[68]

To help limit the imbalance, adjacent feeder stations use different phase combinations; for instance feeder station 1 uses blue-yellow, feeder 2 uses yellow-red, feeder 3 uses red-blue . Direct connection of these adjacent systems would be catastrophic, so a short section of dead OLE – a *neutral section* – is used to keep the phases electrically separate. Trains shut off power before the neutral section, usually by means of an automatic trip, and coast through the neutral section before the power is switched on again (section 11.6.3). This configuration is *single end fed*, with all power coming from one supply point, and uses *tee-feeding*, with each feeder station supplying power in two directions.

Some administrations are now using *Static VAR Converters* (SVCs) or *Static Frequency Converters* (SFCs) to eliminate national grid imbalance and the need for neutral sections. SVCs are solid state devices that provide load balancing and harmonic reduction. SFCs convert three phase AC into single phase AC with a high level of efficiency, so allowing a grid connection to be made at a lower voltage such as 132kV or even 33kV, so potentially lowering the connection cost. When used at concurrent locations along a route - *meshed feeding* - the balanced nature of the SFC output means there is no requirement for neutral sections between them. However, due to their solid state nature, SFCs cannot be driven beyond their rated capacity - if this occurs they will shut down as a precaution against damage. This contrasts with a conventional feeder station, which is typically able to

[67] This figure can be much lower depending on the robustness of the grid at a particular location. For instance the UK High Speed 1 grid connection has an imbalance limit of 0.1%, meaning load balancing technology must be installed at the feeder stations.

[68] This diagram is necessarily simplified; in practice successive feed connections are unlikely to be taken from a single ESI circuit.

operate at 200% of its rated capacity for up to two hours.

Other administrations – notably Russia – use three phase transformers between grid and railway to reduce the imbalance.[69]

The OLE between feeder stations is electrically split into *sections* and *subsections*, allowing sections of OLE to be isolated during planned maintenance or emergency situations. Each running line is electrically separate from the others. For classic feeding, sectioning is maintained at intermediate locations called *Track Sectioning Cabins* (TSCs) or *Track Sectioning Locations* (TSLs). These are the equivalent of the Track Paralleling Hut on a DC railway (section 10.5), and help keep the system impedance down by paralleling all OLE circuits together. The *midpoint TSC* (MPTSC) – so called because it is midway between feeder stations – includes a neutral section which keeps the phases at adjacent feeder stations apart[70].

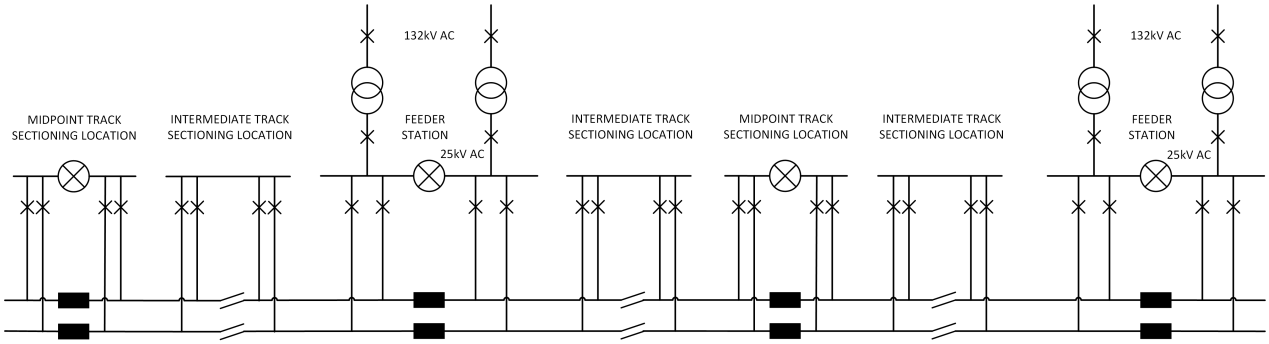


Figure 21: Typical feeding arrangements for classically-fed AC OLE

Typical spacings for 25kV classic feeding are:

- Feeder Station to Feeder Station – 40 to 60 km;
- Feeder Station to midpoint TSC – 20 to 30km;
- Feeder Station to TSC – 10 to 15km.

Spacings are determined by the traffic to be handled, the train performance requirements and the electrical characteristics of the overhead and supply systems. These considerations result in an optimum spacing which it is not often possible to achieve in the real world, and shorter sections are often used to locate the feeder stations at strategic points such as junctions or route intersections. Feeder Stations are usually situated in close proximity to grid substations in order to avoid the high cost of long incoming feeds.

AT systems work on similar principles, but the equivalent of TSCs and MPTSCs are known as *Auto Transformer Sites* (ATS), *Sectioning Auto Transformer Sites* (SATS) and *Midpoint Auto Transformer Sites* (MPATS).

Each feeder station also has a neutral section, allowing the phase split to be moved up and down the railway in emergency feeding conditions. The loss of one incoming grid feed is known as *first emergency feeding* or *N-1 feeding*; the infeed circuit breaker at the feeder station is opened, the *bus section breaker* closed, and the remaining grid feed now supplies the railway in both directions, increasing the feeding distance and load. The system is usually designed to maintain compliant voltage levels in this scenario.

[69] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p42.

[70] TSCs which are not at the midpoint are sometimes differentiated by the term *Intermediate TSCs* (ITSCs).

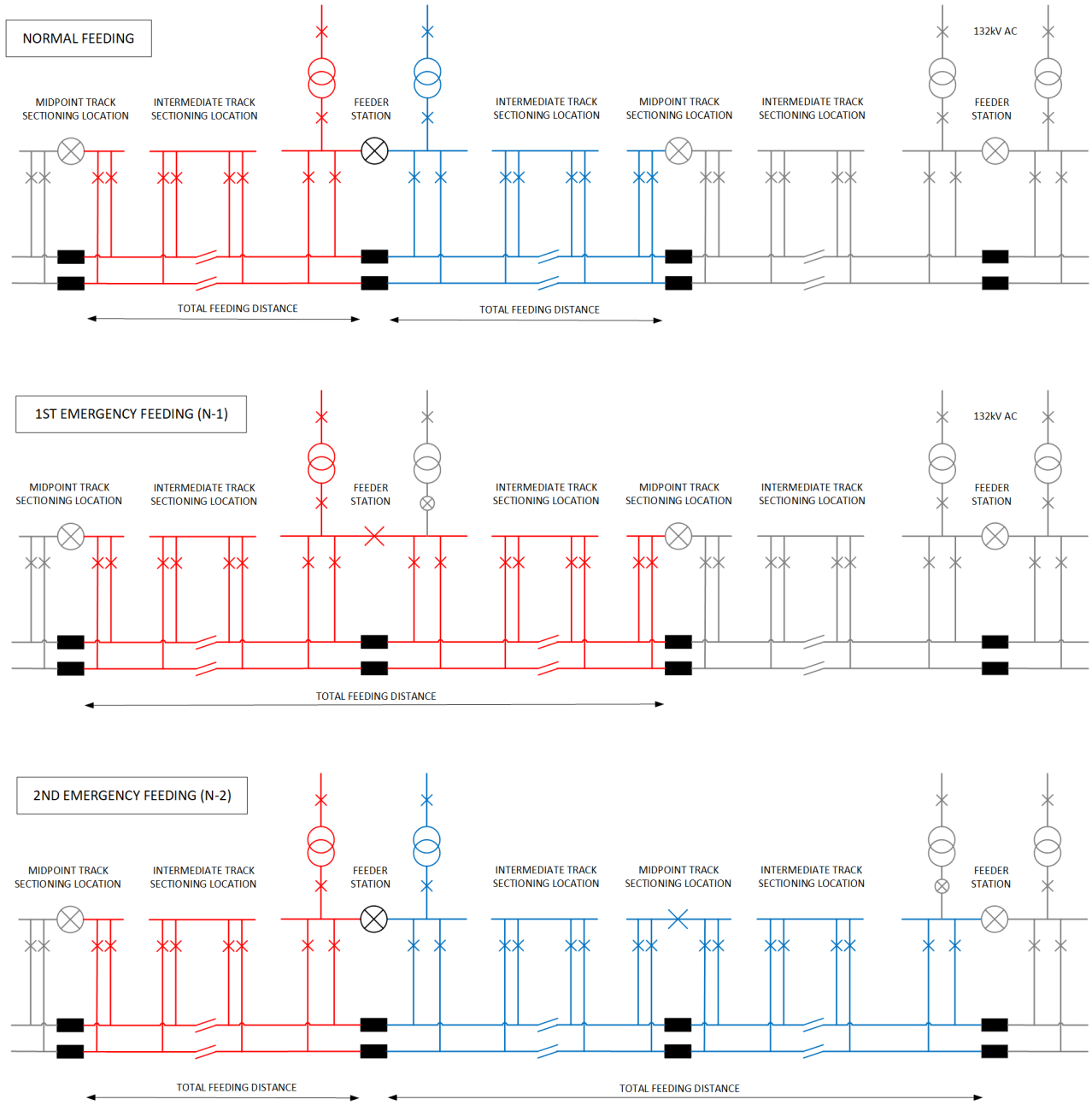


Figure 22: Normal, 1st emergency and 2nd emergency feeding arrangements for classically-fed AC OLE

The loss of an adjacent feeder station grid infeed results in *second emergency feeding* or *N-2 feeding*; in this scenario the midpoint bus section circuit breaker is closed, allowing the feeder station to feed all the way to the adjacent faulty feeder station. Under this scenario voltage regulation may be degraded, and service levels may be reduced.

10.2. AC Supply Equipment

10.2.1. Substation Site Formats

Substation compounds are unstaffed, and take a number of different forms. Until the 1970s the standard format was a fully enclosed brick building housing all the circuit breakers (section 10.2.7), protection (section 10.7.1) and control & monitoring (section 10.7.3) equipment. However this format needed costly civil engineering, so alternatives were sought.

Figure 23: Brick built track sectioning cabin. Perry Barr, UK

In the 1970s the modular steel housing format was developed; this used a steel building module of standard section, typically housing one circuit breaker, so that multiple modules could be bolted together to form a substation.

Figure 24: Modular steel feeder station; note incoming DNO supply on right. Elvanfoot, UK

However this method still required significant foundation work, and so in the 1980s the building was done away with altogether, in favour of *Structure Mounted Outdoor Switchgear* (SMOS). This placed all the circuit breakers in special outdoor housings, mounted on OLE structures with a bare aerial busbar. The control & monitoring equipment was contained in a small building.

However this type of installation created its own problems; water ingress has occurred in circuit breakers, particularly in regions prone to bad weather. In the 1990s the SMOS concept was replaced by the *containerised building* concept, where a complete substation (apart from the transformers) is fitted out in a factory environment and delivered to site in a steel building. This remains the preferred format in the UK, either with indoor switchgear, or more recently with the containerised building housing control equipment for an improved SMOS arrangement.

Figure 25: SMOS track sectioning location - circuit breaker arrowed. Kings Norton, UK

Figure 26: AT feeder station with SMOS switchgear and containerised buildings. St Brides, UK

10.2.2. Supply Transformers

Supply Transformers are used to step voltages down from grid connections at 400kV, 275kV or 132kV to the supply voltage.

400kV *Super Grid Transformers* (SGTs) are typically either an *Oil Natural Air Forced* (ONAF)[71] design, or an *Oil Forced Air Forced* (OFAF)[72] design.

132kV supply transformers are typically of a conventional *Oil Natural Air Natural* (ONAN)[73] design. Off load *tap changing* of ±2½% or ±5% is normally provided to allow the output voltage to be adjusted; other transformers are fitted with remotely controlled *on-load* tap changers to allow this adjustment to be made in service. Typical supply transformer sizes in the UK are 80, 88 and 104MVA for a 400kV to 50kV Auto Transformer (section 10.4.3) feeding supply, and 25 to 26.5MVA for a 132kV to 25kV classic supply (section 10.4.4).

Figure 27: Grid feeding site with 400kV to 50kV Super Grid Transformer on right. Didcot, UK

Where AC supplies are derived from networks operating at voltages lower than 66kV (such as 33kV or 11kV) the transformers are usually purchased by the railway infrastructure owner.

10.2.3. Auto Transformers

Auto Transformers are used to provide 50kV Auto Transformer (section 10.4.3) feeding, and are divided into two types.

Auto Transformers at feeder stations in the UK are typically sized at 80, 88 or 104MVA (oldest to newest). These are of the ONAN type, and have on-load tap changers. Auto Transformers at lineside AT sites remote from feeder stations are typically 15MVA and are also of the ONAN type.

[71] This denotes that the insulating/cooling oil circulates naturally without any forced means, but air cooling uses fans.

[72] Both oil and air are circulated, the former by means of pumps.

[73] Oil circulates naturally, and air cooling is also by natural convention around the radiator fins.

Figure 28: Auto Transformer - note oil-filled radiators and header tank. Hullavington, UK

10.2.4. Isolating Transformers

Isolating Transformers are 1:1 current transformers, used at the interface between AC and DC electrified railways (section 10.11.1). Power ratings are up to 5MVA, and due to the presence of DC voltages, the transformer uses an *air gapped core* rather than the more usual continuous core to prevent *core saturation* from occurring.

10.2.5. Auxiliary Transformers

Auxiliary supplies are used to feed local *Low Voltage* (LV) equipment or as a backup to other supplies, and are taken from the busbar at a substation, or directly from the OLE at a convenient lineside location. Auxiliary supplies can be for:

- Signalling Supplies (typically 650V or 400V);
- Battery charging (typically 110V) for safety-critical substation equipment (section 10.2.8);
- Operation of substation switchgear;
- Lighting and heating for the substation.

These supplies can be derived from the traction supply by means of step down transformers, or direct from a DNO feed. Auxiliary transformers are matched to the load that they feed, and sizes can be anything up to 450kVA.

Figure 29: Auxiliary Transformer. Perry Barr, UK

10.2.6. Transformer Protection

Many administrations require oil-filled transformers to incorporate a means to mitigate the environmental damage done if the oil escapes in the event of a transformer failure. This typically takes the form of a concrete *bund* incorporated into the transformer footing, big enough to house 110% of the total volume of oil in the transformer tank (to allow for water collection from rainfall). These often have a smart bund pump fitted, which will pump excess water from the bund and also detect the presence of oil and raise an alarm.

10.2.7. AC Circuit Breakers

Circuit Breakers are designed to interrupt the traction supply during fault conditions or for routine maintenance. They must be capable of closing and opening (*making* and *breaking*) with both the normal operational currents (*load current*) and the much higher currents experienced during a fault. They must be able to do this many times over their life without experiencing degradation of the electrical contacts. Of particular importance is the ability to quickly extinguish the electrical arc which forms as the contacts move apart.

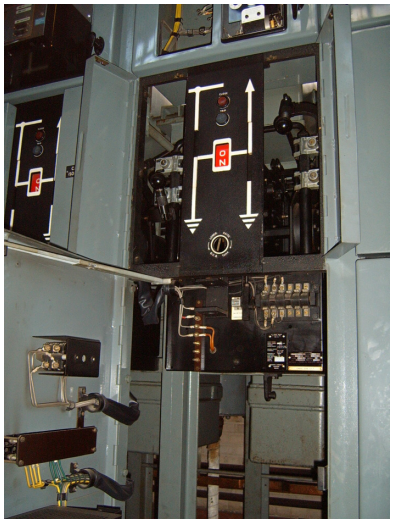


Figure 30: Oil Circuit Breaker. Rugby, UK

When discussing insulation materials in circuit breakers it is important to differentiate between the medium used for the arc chamber and that used to insulate the live parts of the circuit breaker from the earthed casing.

AC circuit breaker technology has advanced significantly in the last 50 years, and this is reflected in the range of circuit breaker types on the railway. In historical order of installation, they are:

- Oil insulated;
- Air insulated;
- Vacuum insulated;
- Sulphur Hexafluoride (SF_6) insulated for both the arc chamber and general insulation;
- Hybrid – vacuum for the arc chamber and SF_6 for general insulation;
- Air insulated (again).

Figure 31: SF_6 circuit breakers. Patford Bridge, UK

Oil Circuit Breakers (OCBs) were used for installations until the 1970s. Oil provides a good electrical insulator and will extinguish the arc quickly while dissipating the heat generated. However, they are heavy and bulky, and are not able to clear faults quickly, while repeated operations contaminate the oil with carbon deposits. These further degrade performance, meaning regular maintenance – which is messy and time-consuming – is required.

Vacuum Circuit Breakers (VCBs) were first used in the 1970s. Their simplified mechanical arrangement means they were thought to be more reliable than OCBs, giving improved interrupting capacity, increased contact life, and requiring less maintenance. They are also significantly quieter and smaller than OCBs, and require less maintenance. In this incarnation a vacuum was used for both the arc chamber and for general insulation.

Sulphur Hexafluoride (SF_6) breakers were introduced because the vacuum in VCBs was proving hard to maintain, with frequent leaks occurring. Initially SF_6 was used for both insulation and arc-extinguishing purposes, but it was found that under arcing conditions the gas breaks down into acidic elements which damage the breaker.

More recent SF_6 designs have used the gas for insulation only, with a vacuum used for extinguishing the arc. However SF_6 is considered to be the most potent greenhouse gas to enter our atmosphere, and the search is on for a suitable replacement. Some circuit breakers use Nitrogen rather than SF_6 as the insulation medium for this reason.

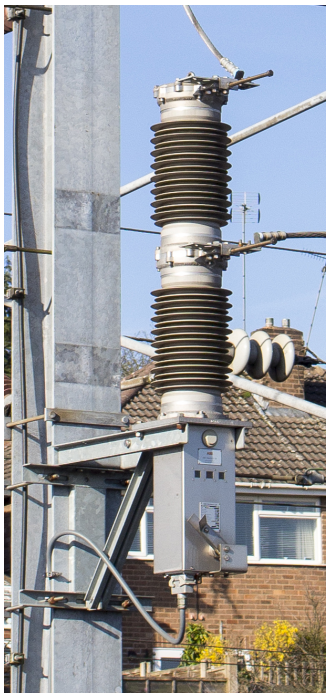


Figure 32: ABB vacuum/Nitrogen SMOS circuit breaker. Kings Norton, UK

Recent developments have looked at the use of resin, or even a modern form of the oil-filled circuit breaker. New UK installations are currently using *Air Insulated Switchgear* (AIS), with air used for general insulation and a vacuum retained for the arc chamber. This requires more space than SF_6 or full vacuum types, but is more reliable and emits no damaging gases.

10.2.8. LV DC Supply Equipment

Substations are typically provided with a local LV DC supply, and the control & monitoring and protection systems (section 10.7) are powered by this supply. This allows the safety-critical systems to continue to function in the event of a failure of the LV AC supply (section 10.2.5), preventing loss of control of the substation.

The DC supply comprises a set of batteries, charged from the LV AC supply. The batteries then feed the SCADA and protection systems - in the UK at 48V DC. In the event of an interruption to the AC supply, the batteries have sufficient capacity to feed the equipment for several hours.

10.2.9. AC Cables

Incoming 400kV or 132kV supplies from the ESI are typically delivered to the railway feeder stations through 400-500mm^2 two-core *concentric pressure* cables. The same type of cable is also used where connections are required between railway feeder stations.

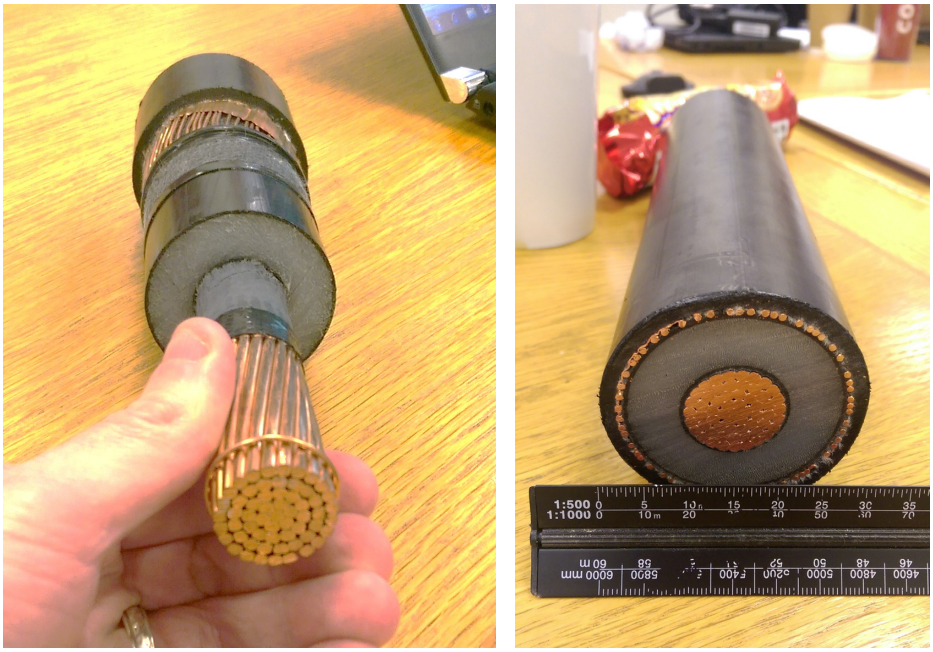


Figure 33: 400mm^2 single core XLPE cable for 25kV feeding

Generally the cables are of the oil-filled type, with some being gas-filled. This latter type has the advantage of a lower *charging current*, and is favoured for tunnel use. Connections from the switchgear to the 25kV overhead contact system are usually formed of 25kV single core solid type cables. All of these cables must be carefully routed to prevent damage to the insulation; the cable will typically be laid in protective troughing, a *minimum bend radius* is specified[74] and additional protection measures may be specified as the cable transitions from trough route onto a mast. HV cables experience large electromagnetic forces during short circuit conditions, and this will result in physical movement and damage unless the cable is mechanically restrained at regular intervals[75].

Figure 34: Sealing ends at a Sectioning AT Site; note the cable armour taken to earth on the middle sealing end. Swindon, UK

The transition from insulated cable to bare wire requires a specialised assembly known as a *sealing end*, which facilitates connection of a bare lugged wire while sealing the insulated cable against water ingress or damage. These connections are built in the field, and the process requires skill and care[76]; they must be electrically pressure tested (section 20.3) to ensure that the insulation strength is maintained.

[74] For 400mm^2 cable, minimum bend radius is typically 1.5m.

[75] The forces generated between parallel cables during a short circuit are proportional to the square of peak current and inversely proportional to distance between the cables. IEC 61914:2015 "Cable cleats for electrical installations"; 28 November 2015; International Electrotechnical Commission. Video of HV cable movement under short circuit conditions is available online at youtu.be/eWPpGtOTuK8.

[76] Installation video is available online at youtu.be/rwIqHW9HmYA.

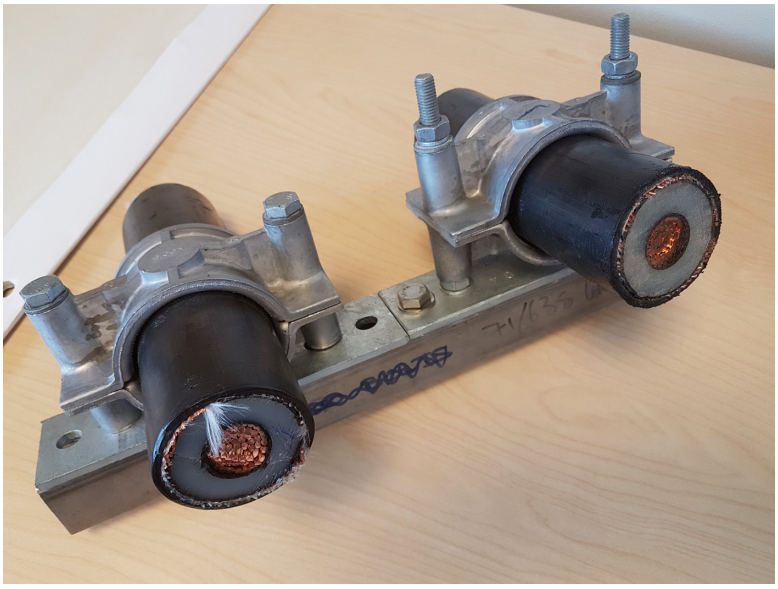


Figure 35: Sample of cable clamping for single core 25kV insulated cables

10.3. AC Sectioning Principles

Sectioning is carefully chosen to give the ability to isolate any OLE section, and is matched to the normal and perturbed working train service patterns.

Crossovers are usually provided to allow trains to transfer from the normal running line to the *wrong direction* line under *perturbation conditions*, which can be for planned maintenance or to deal with unplanned events. Traditionally in the UK insulators have been placed in the OLE (section 11.18) to create subsections which are bridged by normally-closed isolators (section 11.7). When these are opened they allow the OLE to be isolated at a fault or for planned maintenance. The train then runs wrong direction around the isolated subsection.

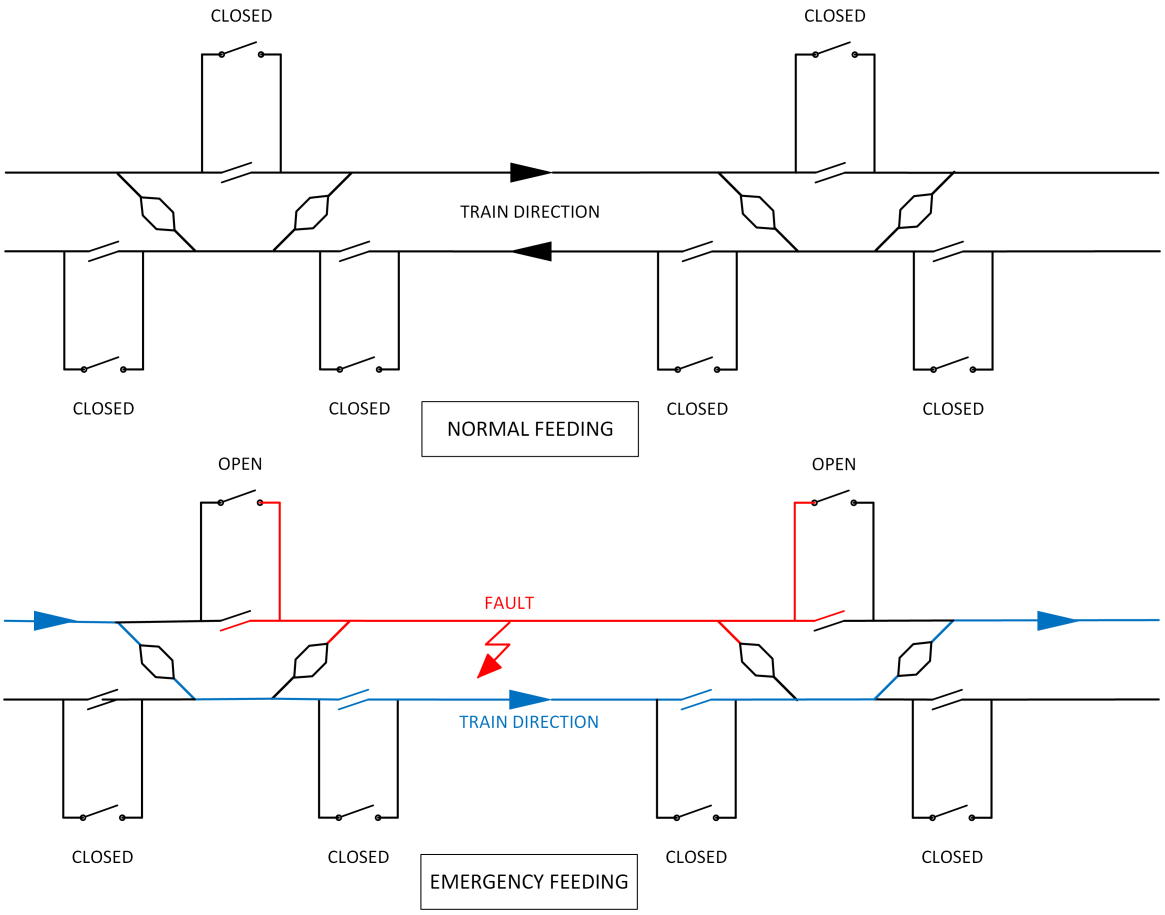


Figure 36: Traditional sectioning of perturbation crossovers

A serious disadvantage of this arrangement is that the *Points of Isolation* are not at the same location on both tracks. This leaves a residual hazard (section 17.12) when one track is isolated; the other remains live and this gives rise to an electric shock risk for workers.

New electrification in the UK is now using parallel isolation points; these also allow the whole junction to be isolated for maintenance, but are less flexible under perturbed working.

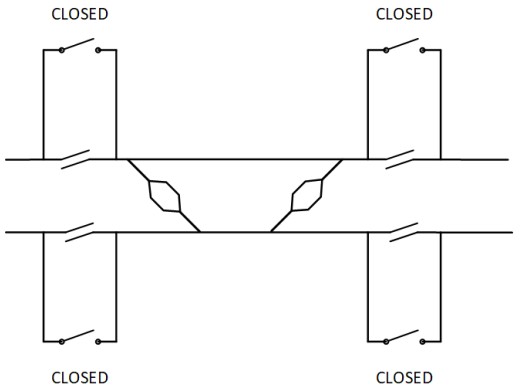


Figure 37: Parallel sectioning of crossovers

Isolators have traditionally been manually operated, requiring switching on site, but remotely operated motorised isolators (section 11.7) are increasingly used.

10.4. AC Feeding and Immunisation Methods

The first OLE systems used the OLE to transmit power to the train, and one or more running rails to return current to the supply point. Since the rails and sleepers form a conductive path to earth, a portion of the return current will flow via the general mass of earth.

In AC systems this was found to be unsatisfactory, due to the large *electromagnetic* (EM) *field* created around the OLE. This drives *inductive coupling* which creates particular problems of *Electromagnetic Interference* (EMI) for safety-critical lineside signalling and telecoms cables, as well as third party cables. This means that on any AC

electrified railway *Electromagnetic Compatibility* (EMC) must be carefully managed, starting with minimisation of EMI at source.

Any conductor carrying current will generate a magnetic field whose strength is proportional to the current, and this field induces a voltage in any nearby cables which is proportional to the magnetic field strength seen by that cable and the length of the cable, in accordance with *Faraday's Law*. The proportion of return current flowing in the rails (as opposed to via earth) decreases exponentially with distance from the supply point[77], and this current is shared between the running rails as a result of cross bonding (section 10.10.1). For this reason each rail generates a much weaker EM field and so the OLE EM field dominates, creating an *induced voltage* in any lineside cables[78]. This *longitudinal voltage* will drive a current that is able to form a circuit via the capacitance of the lineside cable to earth[79]. If the lineside cable has an outward and return conductor (typically formed as a *twisted pair*) then small variations in the longitudinal voltage will create a *transverse voltage* between the conductors. This voltage appears as noise on the cable and creates interference in telecoms systems. Inductive coupling can also affect sensitive magnetic systems in nearby universities, factories and hospitals.

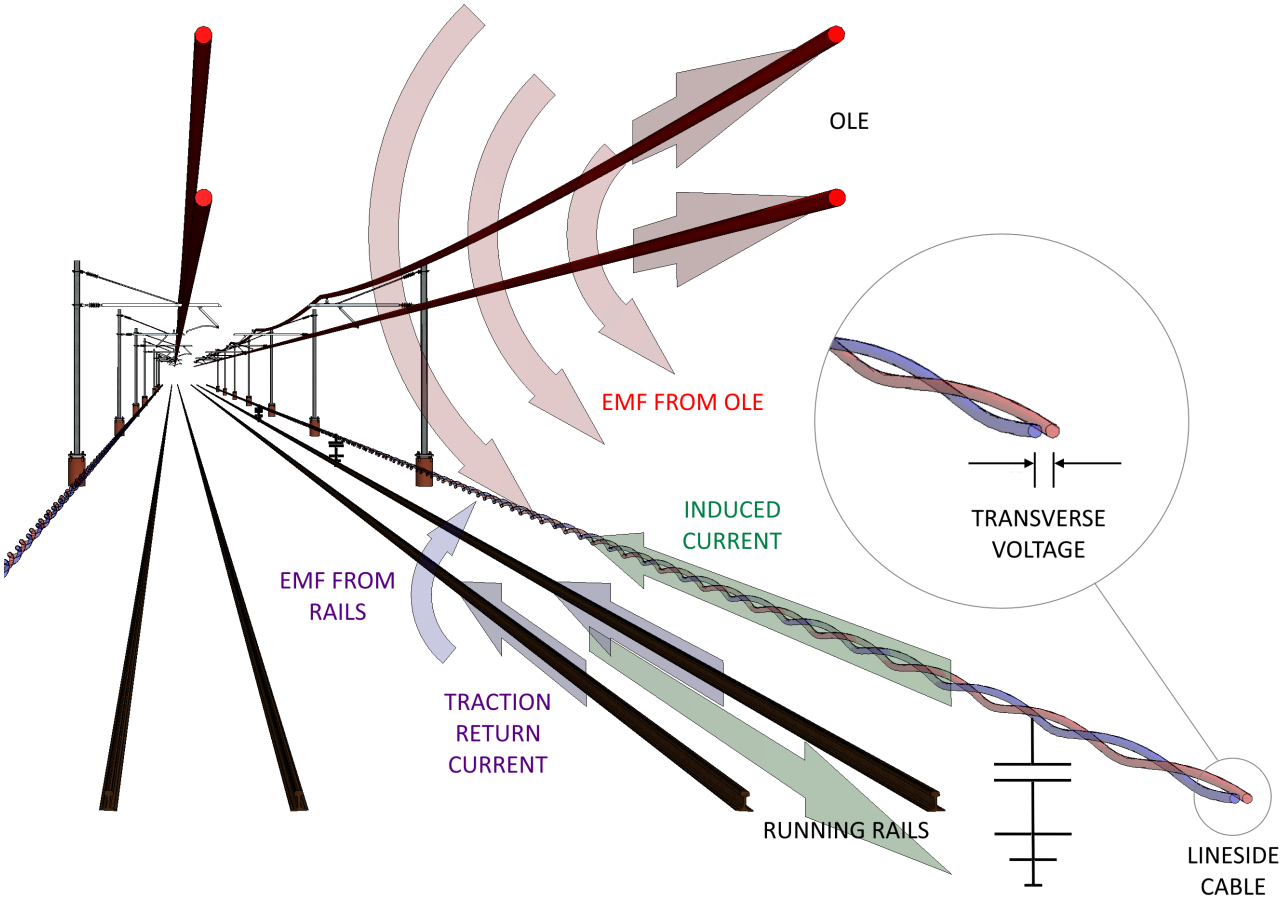


Figure 38: Induced currents in lineside cables with non-immunised OLE

Various techniques have since been adopted to manage this risk.

[77] NR/GN/TEL/31106 "Overview of Electromagnetic Coupling between Traction Systems and Telecommunications Cables"; Issue 1, 2009; Network Rail; section 6.3.

[78] A 200A train load with 10km of parallel lineside cable and no mitigation will induce a longitudinal voltage of 154V in the cable. Ibid.; section 7.1.1.

[79] Ibid.; section 6.6.

10.4.1. Classic Feeding – Return Conductors Only

Where current-carrying conductors interact, the relative direction of the currents determines whether the magnetic fields add or subtract from one another. At any point the magnetic fields can be summed to determine the resultant magnetic field. This interaction is exploited by the *Return Conductor* (RC) system.

The RC runs parallel to the OLE, at approximately the same height, and positioned over the lineside. The RC is insulated from the OLE masts and bonded at regular intervals to the running rail, so providing a measure of current sharing[80]. Because the current in the RC flows in the opposite direction to that in the OLE, and is at equal height, the magnetic field produced by the RC will act to reduce the field produced by the OLE at ground level by around 50%. However, the currents and therefore the fields are not equal, and there is still the potential for interference.

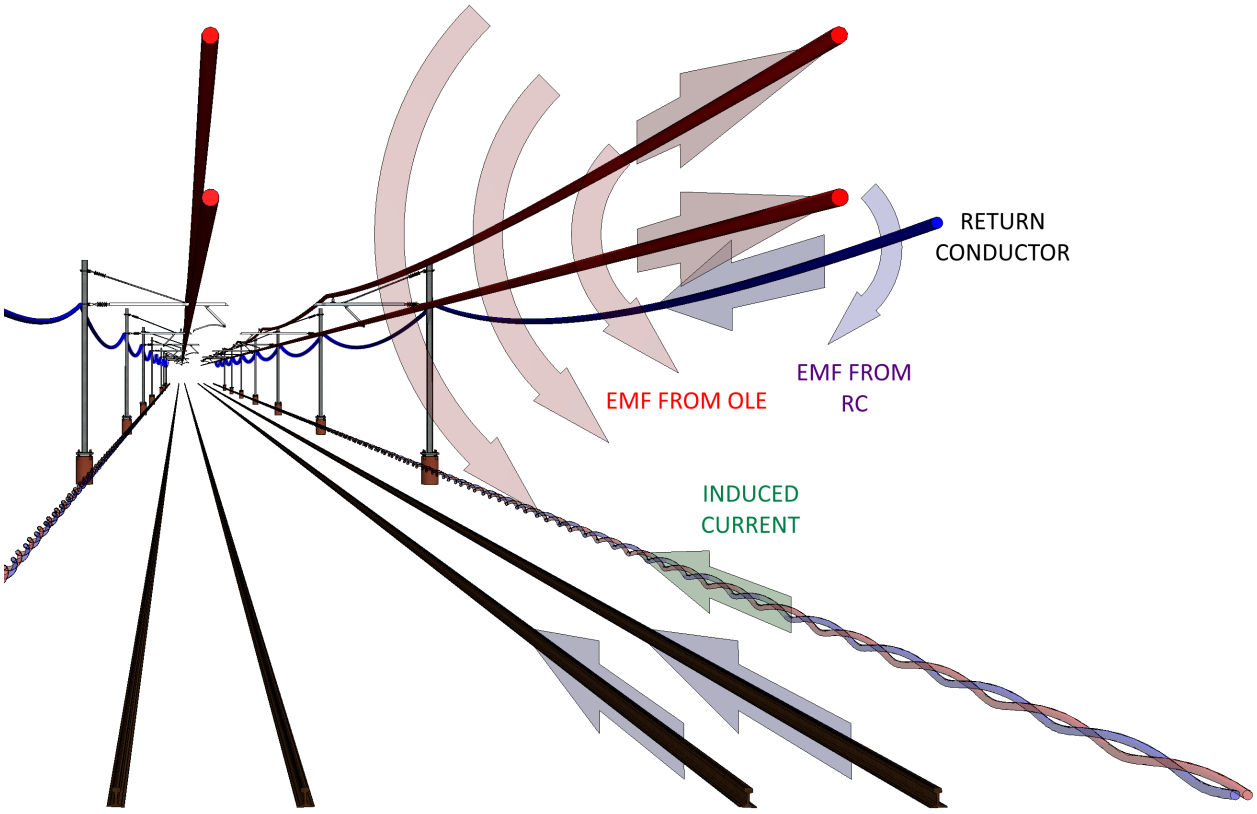


Figure 39: Reduced induction in lineside cables with Return Conductor[81]

[80] Around 35% of return current will still flow via earth, and a 200A train with 10km of parallel cable will induce around 76V. Ibid.; section 7.1.2.

[81] Cable capacitance and cable return flow are omitted on this and all subsequent immunisation diagrams for clarity.

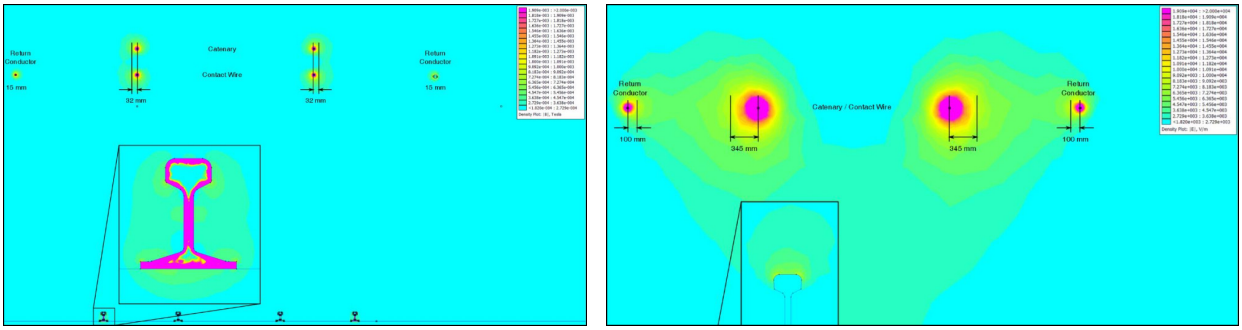


Figure 40: (l-r) Magnetic and electric fields for RC-only railway[82]

10.4.2. Feeding – Return Conductors and Booster Transformers

To maximise cancellation of the magnetic field it is necessary to transfer all of the return current from the rail to the RC. This is achieved by means of a *Booster Transformer* (BT). A BT is a 1:1 ratio current transformer, with the primary winding connected in series with the OLE so that traction current is routed through it. The secondary winding of the BT is connected in series across an electrical break in the RC. The current in the primary induces an equal and opposite current in the secondary winding, and so drives current in the RC; and this current can only come from the rail at a bond connection midway between BTs called the *midpoint connection* (MPC).

This system ensures that almost all return current moves from rail to RC. Since the current in OLE and RC are now approximately equal and opposite, the magnetic fields at ground level largely cancel each other out, and so the BT/RC system provides a large measure of immunisation for lineside cables[83].

Figure 41: Midpoint Connection from RC to traction return rail. Edinburgh, UK

[82] "Report on the Application of the Control of Electromagnetic Fields at Work Regulations 2016", Rafi, Gavrilakis, Hayes; 2016; Atkins/RSSB; appendix A.

[83] A 200A train with 10km of parallel cable will induce around 12V. NR/GN/TEL/31106 "Overview of Electromagnetic Coupling between Traction Systems and Telecommunications Cables"; Issue 1, 2009; Network Rail; section 7.1.3.

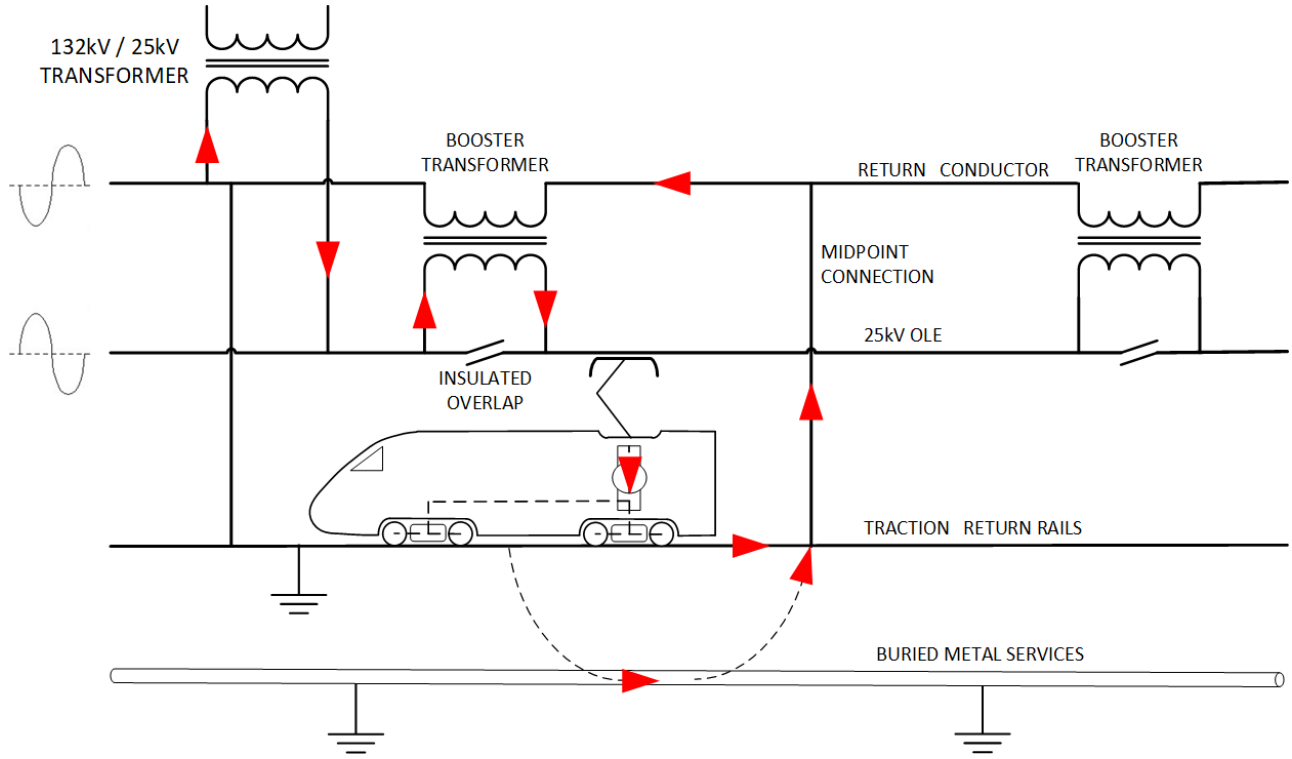


Figure 42: Booster Transformer arrangement for OLE

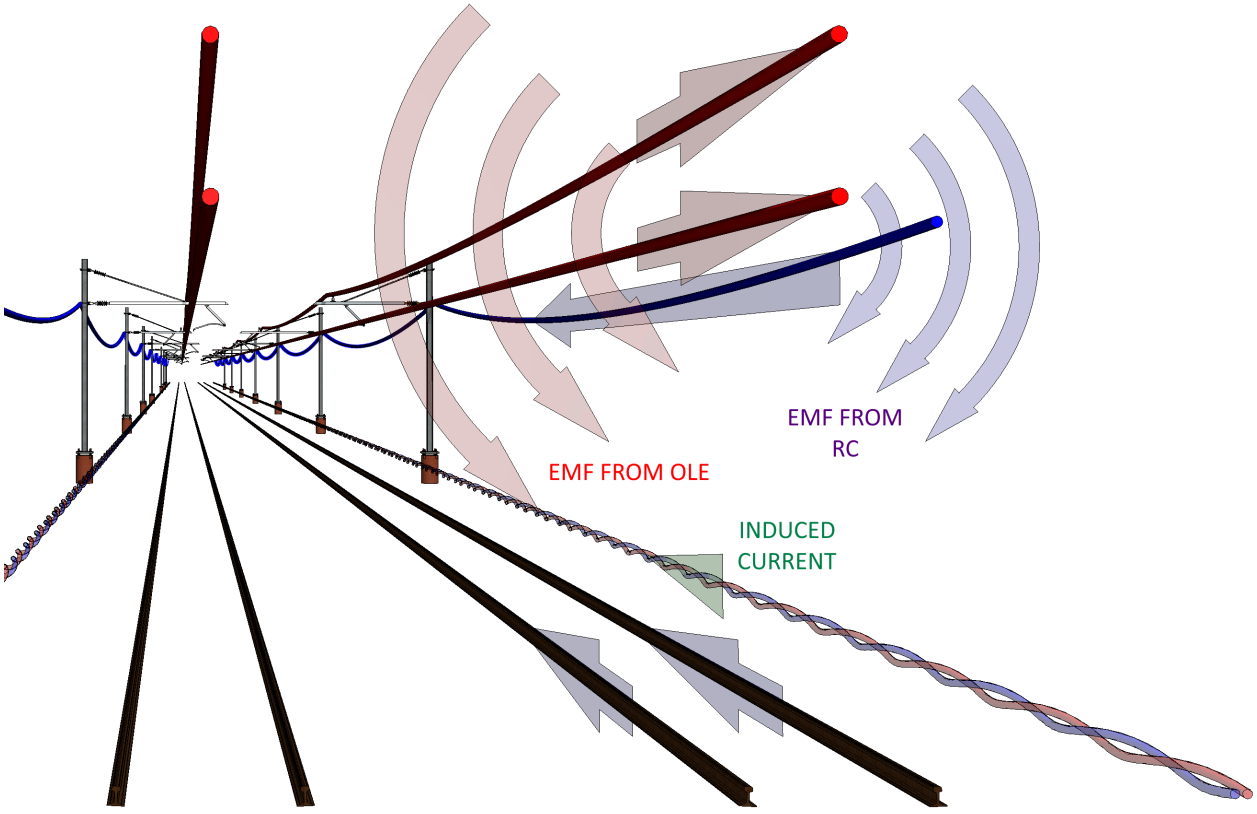


Figure 43: Minimised induction in lineside cables with Return Conductors and Booster Transformers

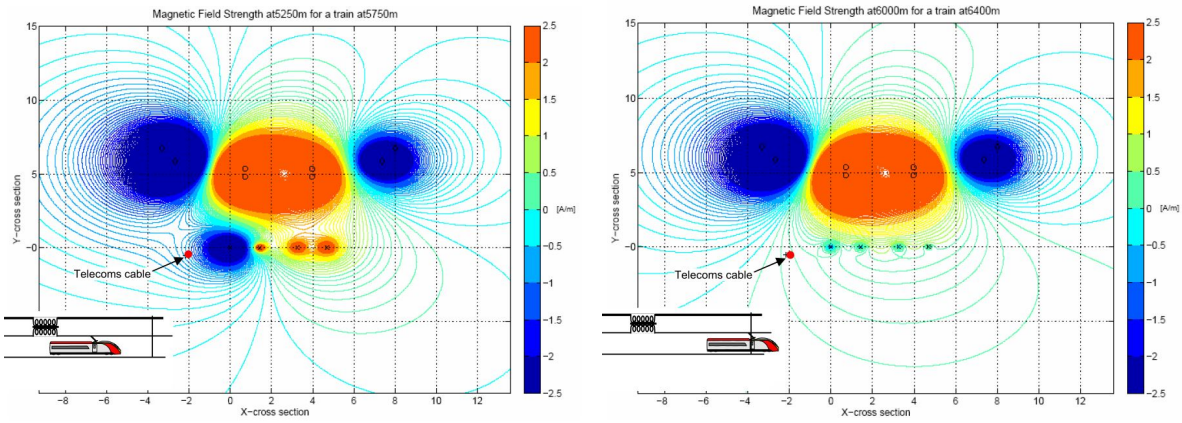


Figure 44: (l-r) Magnetic field strengths with 100A train load; at location between BT and MPC, and at MPC location[84]

Booster Transformers are typically located every 5km, and OLE overlaps (section 11.4) are used as a convenient point for a break in the OLE.

Figure 45: Booster Transformers - note primary winding connection to OLE and secondary to RC. Selly Oak, UK

Booster transformer systems have two major disadvantages: the transformers require regular checks, particularly for contamination of the insulating oil; and they increase the impedance of the system, thereby limiting the power capacity.

The BT/RC arrangement has been used widely across Europe, Asia and the UK, but there remain a large number of legacy RC only routes.

[84] Ibid.; section 7.1.3.

10.4.3. Auto Transformer Feeding

There are practical limits to the amount of power that a classic feeding system can deliver as volt drop losses increase. In particular, the move to higher passenger speeds requires a system with much higher power availability. The *Auto Transformer* (AT) system was pioneered at Philadelphia in the US in the early 20th century, using 36kV transmission and 12kV supply. It was then used on the Shinkansen at 60kV:30kV, before being introduced in Europe for TGV routes at 50kV:25kV. This is now the standard configuration for new high speed lines, and the details below are based on this configuration.

In any electrical circuit with a fixed load, power is proportional to V^2, and so there is more power available in a 50kV system than in the classic 25kV feeding system. Alternatively, since the current is halved for the same power, the same electrical load can be serviced with fewer feeder stations spaced further apart.

At the heart of the system is the Auto Transformer itself. This transformer works differently to a conventional one, since it has only one winding wound onto a laminated core. This primary winding is divided in two by taking a secondary *centre-tap* at the midpoint of the winding; this means that a part of the winding is common to both primary and secondary sides. The *primary current* flowing in the primary winding creates an electromagnetic field in accordance with Faraday's Law, and as with any transformer this creates an electromotive force (voltage) in the half of the winding connected to the secondary, that drives a *secondary current* in the opposite direction to that of the primary current, in accordance with *Lenz's Law*. So when under load, part of the load current through the winding is obtained directly from the supply, and the rest is driven by the action of the transformer.

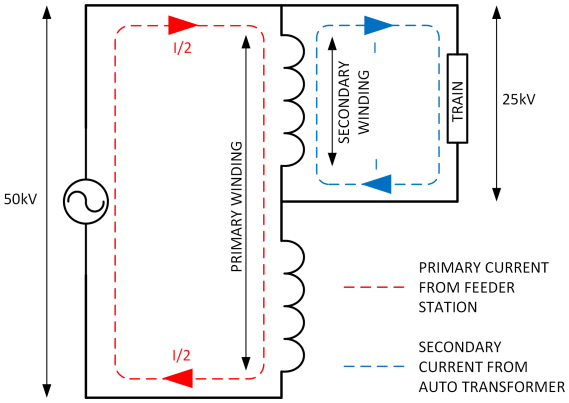


Figure 46: Basic Auto Transformer operation showing loop currents

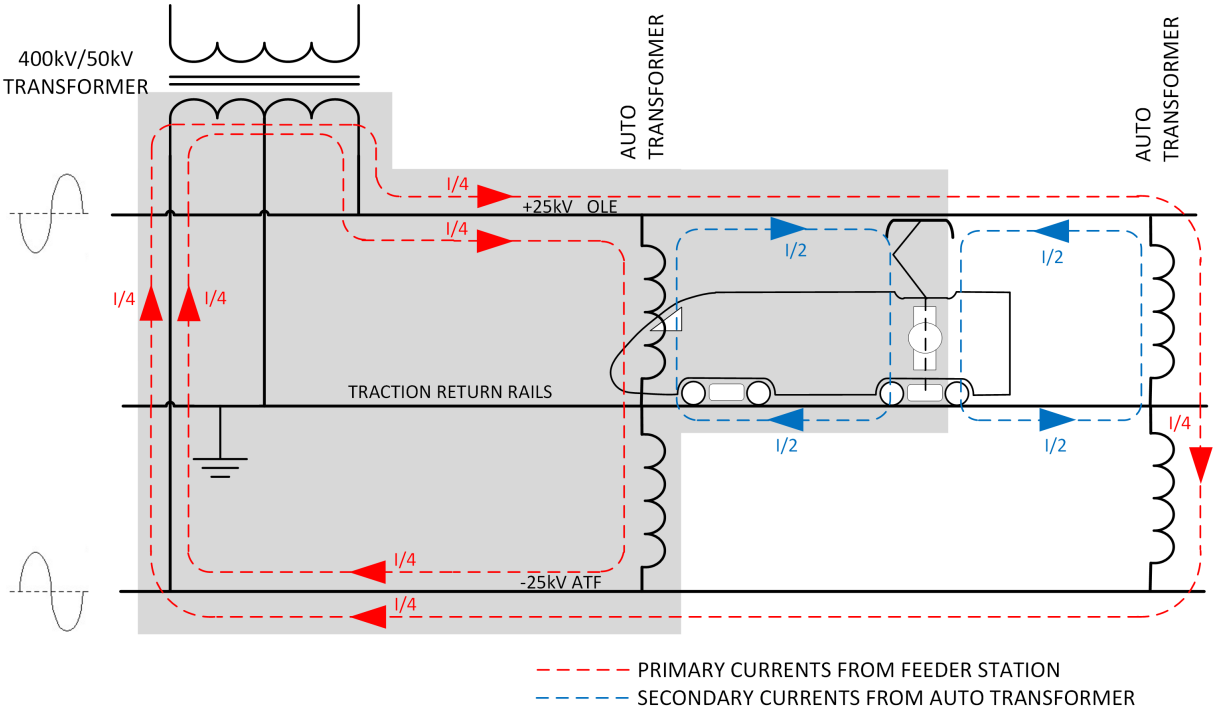


Figure 47: Auto Transformer arrangement for OLE, showing loop currents for a train drawing I amps. Shaded region represents previous figure

The system is supplied from a 25kV-0V-25kV centre-tapped voltage transformer, with the OLE fed from one half of the winding at +25kV, and an *Auto Transformer Feeder* or ATF (also known as an *Auxiliary Feeder* or AF) fed from the other half at -25kV. The traction return rail (section 10.10.1) is connected to the 0V centre tap.

The auto transformers are arranged in parallel along the railway, with the OLE fed from one end of the primary winding at +25kV, and the ATF fed from the other end at -25kV. The traction return rail is connected to the centre tap. The secondary winding is formed from the section of winding between the OLE and traction return rail.

The primary current, driven by the 50kV primary circuit, is supplied along the OLE to the AT and returns via the ATF. Ignoring volt drop in the system, the paralleled ATs all have the same 50kV primary voltage. Since the primary winding has twice as many turns as the secondary, the primary current drives a secondary current which is twice as large and moves in the opposite direction. The secondary circuit of each AT is therefore able to deliver twice as much current to the train as that which flows in the primary circuit, but at a voltage of 25kV. This is an essential requirement of any AT system, which must interface with classically-fed systems (section 10.4.4) and 25kV trains.

Meanwhile the current in the OLE is the sum of the primary currents of all ATs in parallel, plus the secondary current required by the train; and the current in the ATF comprises only the sum of the primary currents. This allows the ATF to carry out a similar immunisation role to the Return Conductor. AT sites are typically located every 5 to 10km, and can be thought of as acting as proxy feeder stations which take a supply from a 50kV ring and transform it to 25kV.

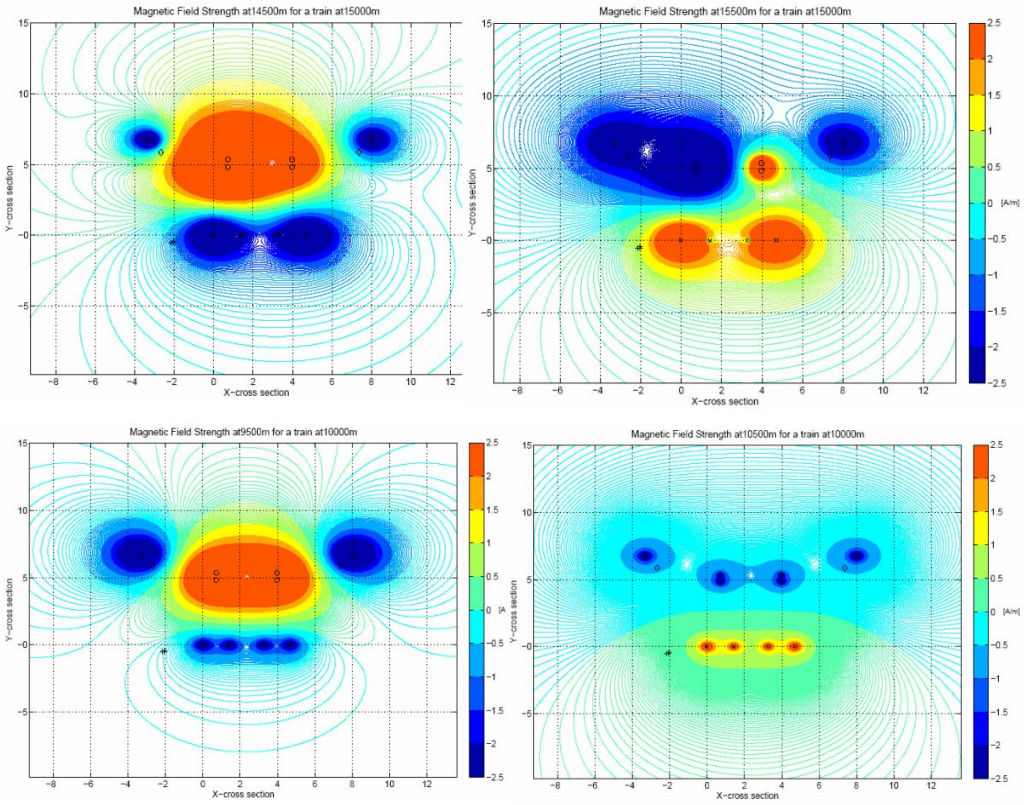

Magnetic Field Strength at14500m for a train at15000m
Magnetic Field Strength at15500m for a train at15000m
Magnetic Field Strength at9500m for a train at10000m
Magnetic Field Strength at10500m for a train at10000m
Y-cross section
X-cross section
[A/m]

Figure 48: (top to bottom) Magnetic field strengths with 100A train load; midway between Auto Transformers, and at an Auto Transformer[85]

The additional 25kV ATF conductors create additional design challenges, since 25kV clearances must be

[85] Ibid.; section 7.1.4.

maintained for ATF to earth, but also 50kV clearances for ATF to OLE. This can be a particular problem through limited clearance overbridges and stations.

The AT system is widely used on high speed systems worldwide, and in the UK it is installed on HS1 and GWML. It has also been retrofitted to the WCML and ECML to increase power capacity, and new retrofitment is under way on the GEML.

10.4.4. Boosterless Classic Feeding

In recent years the BT/RC system has been deprecated in the UK, in favour of *boosterless classic* feeding. This arrangement removes all booster transformers and return conductors in favour of a simple out-and-back feeding arrangement. Immunisation is instead provided by means of a Return Screening Conductor (section 10.4.5).

10.4.5. Mutual Screening and Return Screening Conductors

The *Mutual Screening Conductor* (MSC) and *Return Screening Conductor* (RSC) systems exploit another feature of electromagnetic fields interacting with conductors. Both take the form of an insulated cable placed immediately next to the cable which requires immunisation – usually in the signalling trough route.

When used as an MSC, this cable is earthed – in the UK, this is done every kilometre using a 4Ω earth connection. The EM field created by the OLE then acts on the MSC, setting up a magnetic field which opposes that of the OLE in accordance with Lenz's Law. Current will then begin to flow in the MSC, in the opposite direction to the current in the OLE. The MSC cable size is chosen with a larger cross sectional area than the lineside cables to provide a lower impedance, so the AC induced current in the MSC will be correspondingly higher than that in the lineside cable.

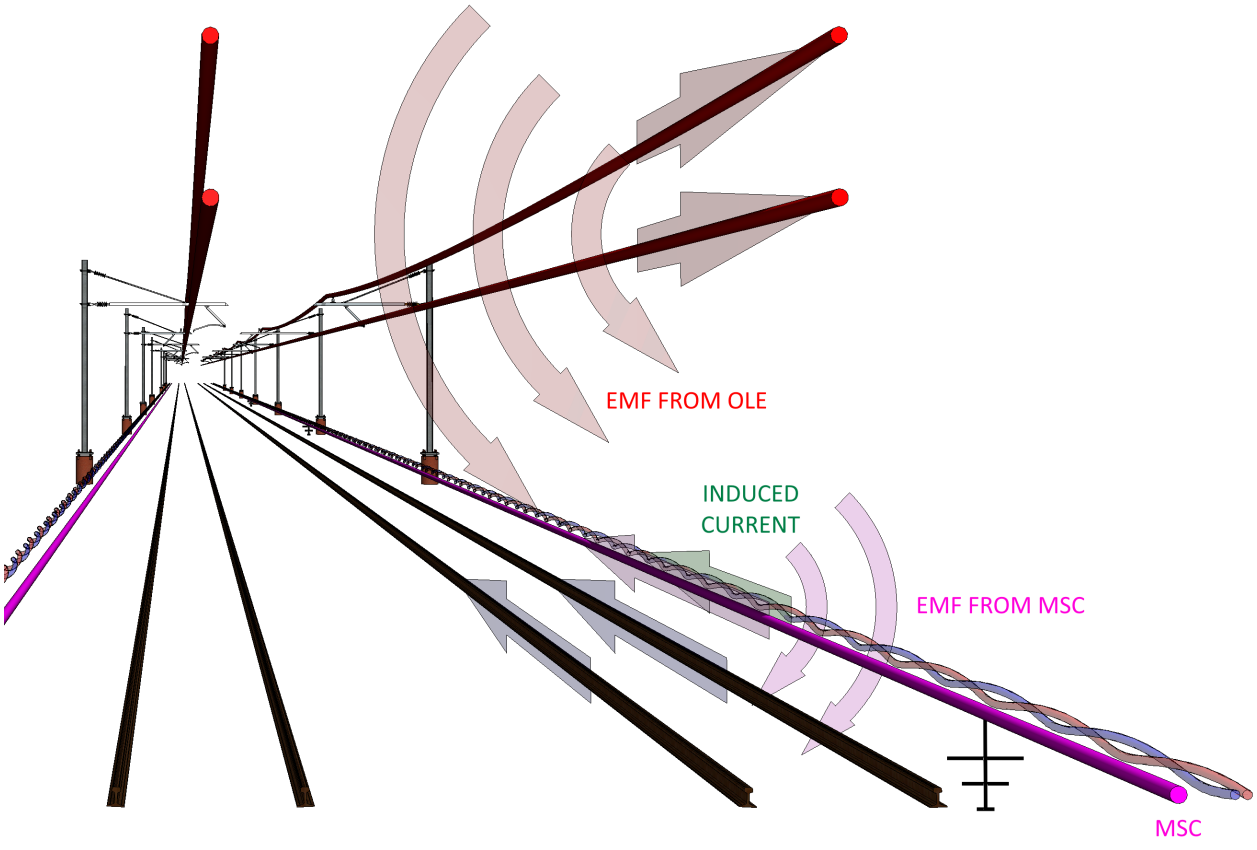


Figure 49: Reduced induction in lineside cables with Mutual Screening Conductor

The induced current in the MSC then creates its own magnetic field in the trough route which induces a voltage

in the lineside cable; one which opposes that induced by the OLE. This works provided that the MSC has low impedance to earth, and is physically close to the lineside cable.

MSCs in the UK are typically PVC sheathed 19/4.22 aluminium cable (section 11.16.5). This provides a screening factor of about 0.69, meaning the voltage induced on the LV cable is reduced by 31%. Although the current induced by the MSC is lower than that induced by the OLE, the reduction can sometimes be sufficient to remove the safety risk.

The disadvantage of the MSC is that it needs earth farms at regular intervals along the railway, and provides only limited screening. The RSC operates in the same way as an MSC, but is instead connected to the traction bonding system, typically at the cross bond locations (section 10.10.1). This removes the expensive earth farm requirement and provides significantly better screening than an MSC – for example the same 19/4.22 Al cable provides a screening factor of 0.33, reducing the induced voltage by 66%.

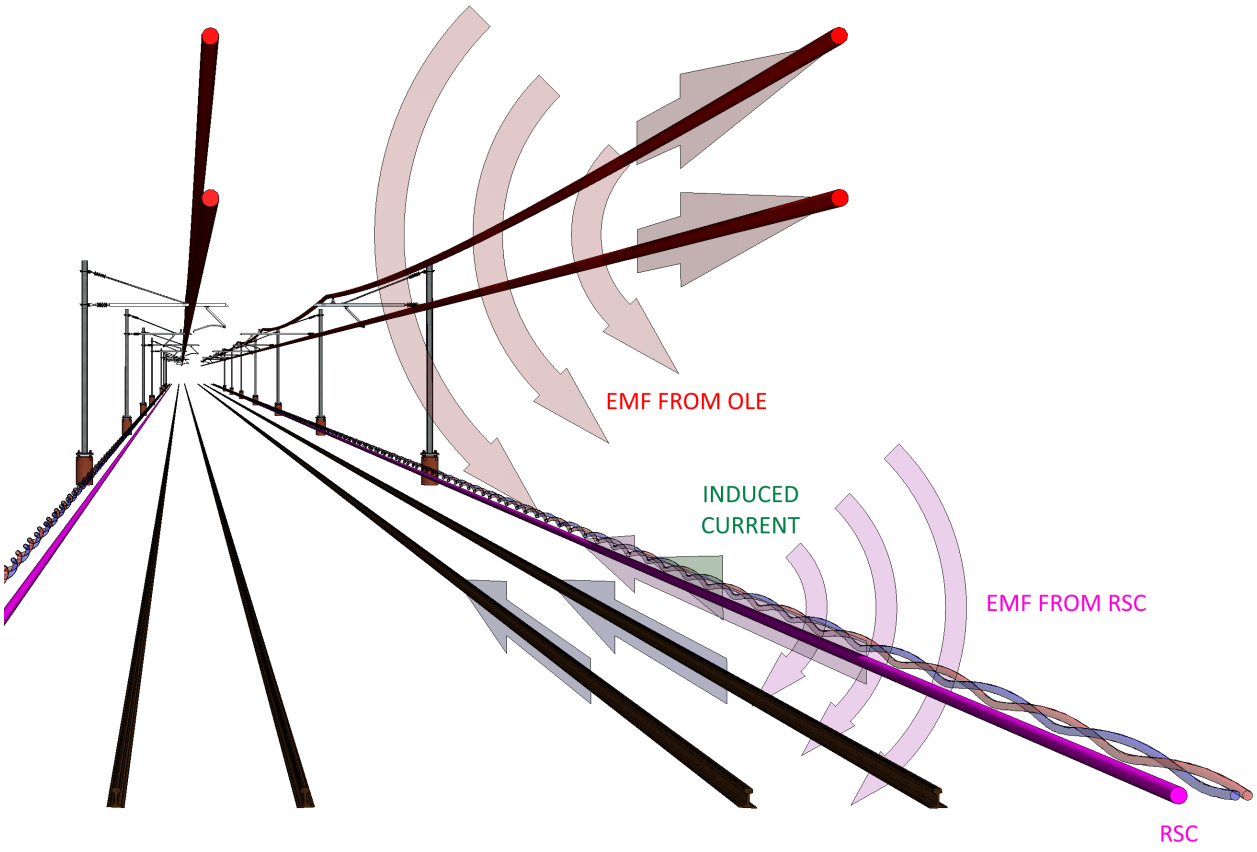


Figure 50: Minimised induction in lineside cables with Return Screening Conductor

RSCs are now being used in the UK with Boosterless Classic (section 10.4.4) and AT feeding (section 10.4.3) systems. Although the ATF in an AT feeding system provides a measure of EM cancellation, an RSC is also used to allow lineside circuit lengths to be significantly longer.

10.5. DC Supply Principles

DC systems have historically been constrained to lower supply voltages (up to 3kV) due to the expense and availability of *rectification equipment* (which converts AC current to DC), and the difficulty in breaking DC fault current. This means the system suffers from a large volt drop as a percentage of the supply voltage, and substations must be placed closer together (1.5km to 6km apart). The cost of providing a direct feed from the DNO at each location would be prohibitive, so mainline DC railways usually have a dedicated HV trackside feeder system to provide power to the substations. These feeder rings are typically at 66, 33, 22 or 11kV, fed

from a 132kV DNO infeed. The HV supply is then transformed down and rectified at each substation to provide power to the railway. The rectifier is fed with all three phases, meaning there is no imbalance on the DNO supply or requirement for neutral sections, and is usually of the 6 or 12 pulse type, to minimise the *ripple voltage* which is a feature of all rectifier outputs. The removal of any phase imbalance allows DC systems to be *double end fed*, which helps to raise voltages midway between substations. DC substations have outputs varying from 1MW (for tram systems) to 10MW (for mainlines)[86]. Regenerative braking is only possible on DC systems with the addition of a DC to AC *inverter* in parallel with the rectifier.

Many mainline DC systems also have *traction feed wires;* these run at the same voltage as the OLE and connect to it at regular intervals. They are usually suspended from the OLE structures and help to reduce the system impedance and raise line voltage.

Tram systems are usually compact enough not to require HV feeder rings, which would in any case be difficult to safely configure in busy street environments. They do however usually have traction feed cables buried in lineside ducts for safety reasons, and brought up the mast at regular intervals to connect to the OLE.

10.6. DC Sectioning Principles

Switching is carried out at intermediate *Track Paralleling Hut* locations. These help keep the system impedance down by paralleling all tracks together.

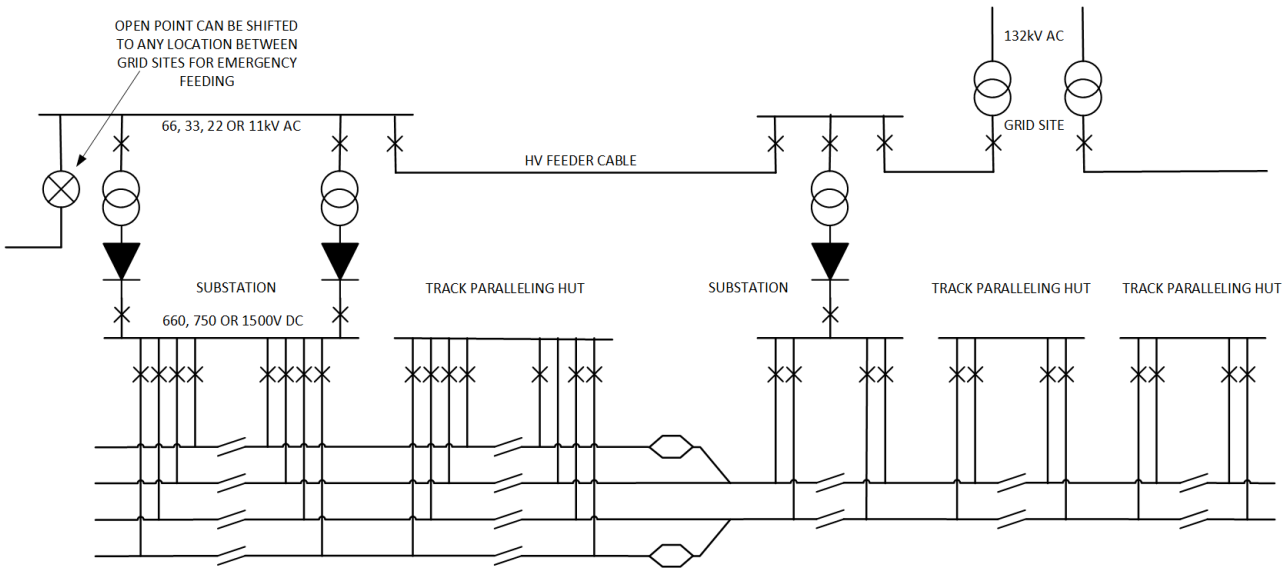


Figure 51: Typical feeding arrangements for DC OLE

10.7. Protection, Monitoring and Control

10.7.1. Fault Protection

OLE systems are vulnerable to a large number of faults. These faults result in currents that are much larger than those caused by normal operation, causing considerable damage if the supply is not quickly disconnected. To prevent this damage an *electrical protection system* is used to clear faults by opening the circuit breakers feeding into the section.

Any system of protection should:

[86] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p38.

- Be able to differentiate between load current and fault current;
- Be sufficiently sensitive to detect a fault in its early stages;
- Be very reliable in operation – the simpler and more robust the design the better;
- Discriminate between currents fed to faults within the electrical section being protected, and current passing through to a fault in another section.

This section focuses on fault protection of an AC system.

10.7.2. Classic Protection

Classic protection has been used on all but the most recent electrification schemes. In this configuration OLE is split into sections that are fed from a single phase, single end-fed AC supply (section 10.3). Each feed is routed through a circuit breaker.

Attached to the feed by means of a *Current Transformer* (CT) and *Voltage Transformer* (VT) is a *protection relay* which looks continuously for faults, by measuring both voltage and current, and then calculating the impedance of the section that it is feeding. This is known as *impedance* or *distance* protection. It exploits the fact that fault current will usually flow through several circuit breakers between the fault and the feeder station, thus giving the opportunity to provide time delayed backup protection. The system is also impervious to voltage fluctuations, which would fool a simpler overcurrent-based protection system and cause *nuisance tripping*. Importantly, a distance relay will only detect fault current flowing in one direction.

Figure 52: Alstom P40 distance protection relay

Distance protection in the UK is configured with three *zones* of protection:

- Zone 1 is set to trip instantaneously, and is set to the impedance of the initial section less a calculation tolerance - so that zone 1 typically detects faults up to 85% of the way along the protected section;
- Zone 2 sees approximately 70% of the adjacent section and has a small time delay;
- Zone 3 sees all of the following section with a larger time delay.

To understand how this works, consider a two track railway consisting of three electrical sections, each protected separately and capable of isolation by a circuit breaker at each end of the section:

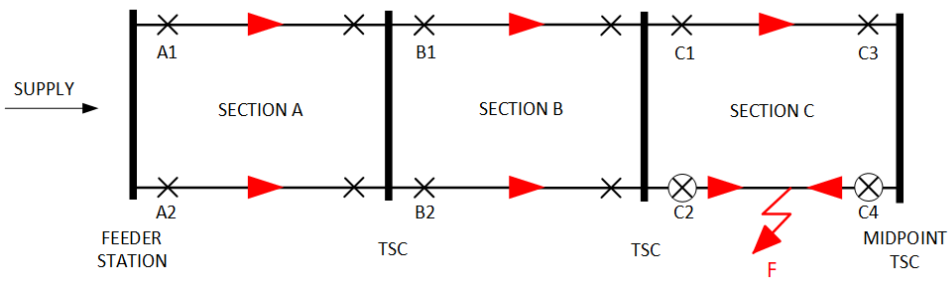


Figure 53: Detection of a fault using distance protection

During a fault the impedance (Z) of the faulted section will be significantly lower, since Z = V/I and I is now fault current rather than traction current.

The fault at F is a section fault relative to Section C, but a through fault relative to Sections A and B. Thus the protective devices on Sections A and B should not trip their respective circuit breakers, whilst the protection on Section C should detect the lower impedance and open its circuit breaker.

If circuit breakers C2 and C4 do not clear the fault within the specified time, then the protection on section B will cause circuit breakers B1 and B2 to trip. Similarly, circuit breakers A1 and A2 will trip if all the affected circuit breakers in section B do not.

In addition to impedance protection, *overcurrent* and *undervoltage* protection may be provided. Overcurrent protection is typically provided using an *Inverse Definite Minimum Time* (IDMT) relay. The speed with which this relay operates is inversely proportional to the magnitude of the overcurrent - an ideal characteristic for overcurrent protection - but like all electromagnetic devices, it has a minimum operating time.

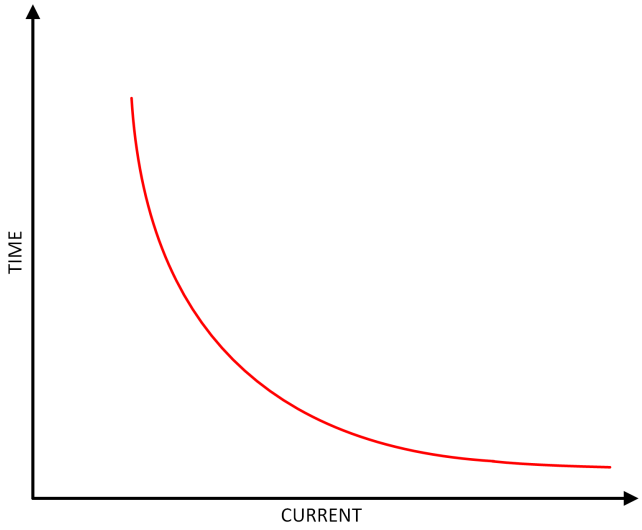


Figure 54: Inverse current-time relationship for IDMT relay

10.7.3. Classic Control and Monitoring

The circuit breakers at feeder stations, TSCs and AT sites are under the control of the *Electrical Control Room* (ECR). This is a control centre which supervises operation and maintenance of the OLE and the power & distribution system. A telecommunication system known as *Supervisory Control and Data Acquisition* (SCADA) is used to monitor and control circuit breakers remotely.

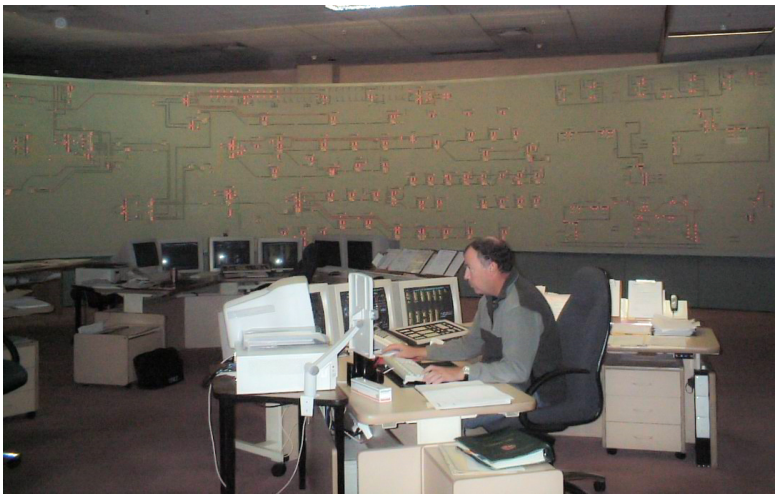


Figure 55: ECR display screens. Melbourne, Australia

Traditional railway SCADA uses a *Time Division Multiplex* (TDM) system which polls the SCADA *outstation* or *Remote Terminal Unit* (*RTU*) at each feeder station in turn, interrogating the state of each circuit breaker. Any change in state or alarm is relayed back to the ECR. Similarly the ECR can send an instruction to a particular circuit breaker to open or close in the event of a fault or maintenance. The *Electrical Control Operator* (ECO) is therefore able to monitor and control the whole system from a set of display screens at a central terminal. Motorised isolators and/or load break switches (section 11.7) under ECO control may also be provided at key locations if fast perturbation management is required.

10.7.4. IP-Based Control and Monitoring

TDM-based SCADA is now being superseded by a computer-based system using *Internet Protocol* (IP) based networks and computer outstations in each substation. These sites are capable of communicating with each other to determine and clear faults, without needing direction from the central ECR software; instead the control and monitoring is carried out at a local substation-to-substation level. This is done by means of *Generic Object Oriented Substation Event* (GOOSE) messages.

This system is captured in a new European standard[87], and is now being used to significantly improve the detection and clearance of faults, while reducing switchgear costs.

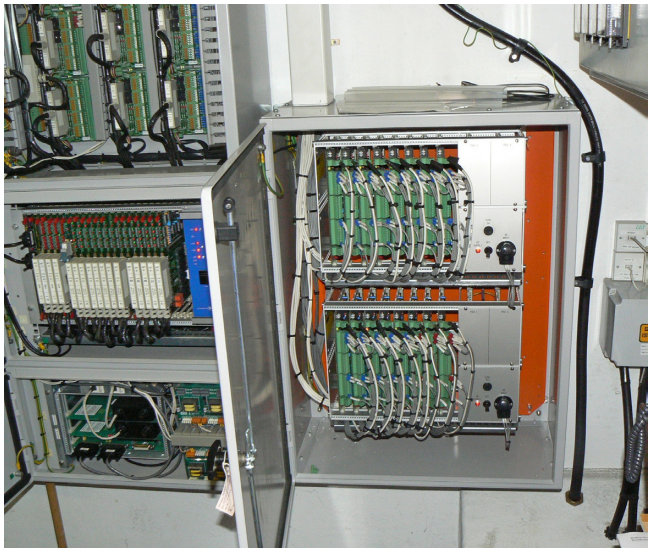


Figure 56: SCADA outstation. Hayes, UK

10.7.5. Rationalised Auto Transformer System Protection

The classic protection system (section 10.7.3) was borne out of the necessity for each substation to be self-sufficient in detecting and clearing faults. The ability of IP-based substations to communicate with each other - without reference to the ECR - has recently led to the development of the *Rationalised Auto Transformer System* (RATS) protection scheme.

This is currently only used on auto transformer (section 10.4.3) systems in the UK, taking advantage of the tee feeding at AT sites to work in a radically different way to classic protection schemes.

Faults are cleared in a four step process:

- Detect fault within the protected feeding area;
- Open all circuit breakers for all lines and all electrical sections - both OLE and ATF;
- Open load break switches (section 11.7) feeding the faulted section;
- Reclose all circuit breakers (other than those directly feeding the fault) and resume normal feeding on unfaulted sections.

By adopting these principles, the number of circuit breakers in the system is significantly reduced - outgoing feeders at the AT sites are fed using cheaper load break switches rather than circuit breakers.

[87] IEC 61850:2018 "Communication Networks and Systems for Power Utility Automation"; International Electrotechnical Commission; 2018.

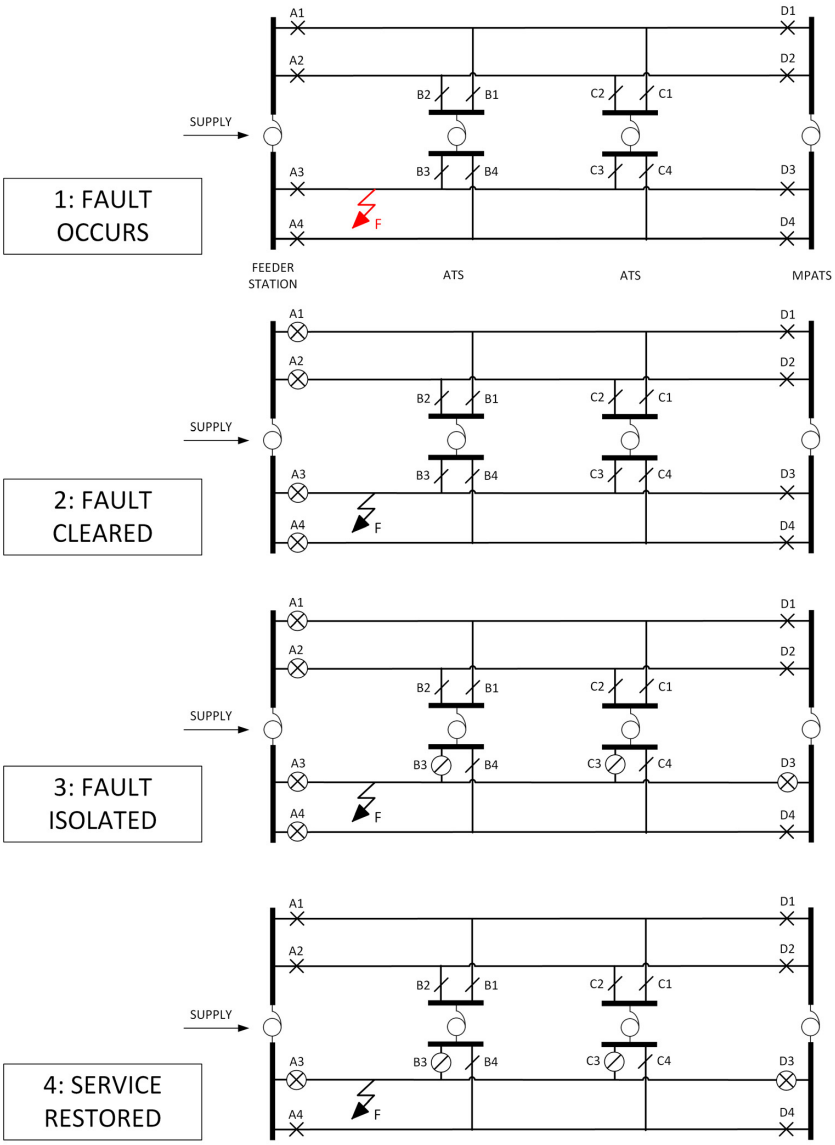


Figure 57: Typical RATS fault clearing process for a two track railway

In the two track section above, a total of 8 load break switches are provided. If a fault occurs at F, within the first 50ms, the fault is detected. Between 50ms and 150ms, all feeding circuit breakers - A1 to A4 - are opened. Both tracks and ATFs are now isolated.

With all current flow stopped, it is safe to open the load break switches feeding the faulted section, B3 and C3; these switches cannot break fault current, which is why it is necessary to open all circuit breakers first. Fault isolation occurs between 150ms and 5s after the fault has occurred.

With the faulty section isolated, circuit breakers A1, A2 and A4 are now reclosed and railway operation is restored within 5s of the fault occurring. The whole process is fully automated and does not require ECO intervention.

While having some clear advantages over classic protection schemes, RATS does rely on sophisticated and specialised logic in the IEC61850 code, requiring a significantly different skill set to traditional protection systems. The system also results in an entire railway being isolated for a short period before service is restored.

Work is now under way to apply the cost-saving principles of rationalised protection to new boosterless classic (section 10.4.4) electrification schemes in the UK.

10.7.6. Interlocking

The power supply system is provided with *interlocking* at both a circuit and system level, to protect the electrification system from operational errors, and to help ensure safety and reliability.

At the circuit level, both electrical and mechanical interlocking is provided within each substation; depending on the choice of switchgear (section 10.2.7), the interlocking ensures that equipment is operated in the correct sequence - for instance, to prevent an earth switch being closed onto a closed (and so potentially live) circuit breaker. A mechanical interlock provides a physical barrier preventing this occurring, whereas an electrical interlock is a control circuit that prevents the operation being carried out.

At the system level, interlocking is provided to assist with operation of the system, but also to ensure safety between the ESI electrical system and that of the railway. For instance at a typical feeder station with two incoming ESI supplies, a *two out of three* interlocking is applied to the incoming circuit breakers and to the bus section that separates them (section 10.1.3). This permits any two of the three circuit breakers to be closed at any point in time, so preventing the incoming supplies being connected together through the busbar and potentially overloading and damaging both the ESI and railway systems. Bus section circuit breakers are also provided with *dead bus switching* which only permits the bus section circuit breaker to be closed if one of the busbars is de-energised; this is an additional barrier to accidental connection of the two incoming circuits.

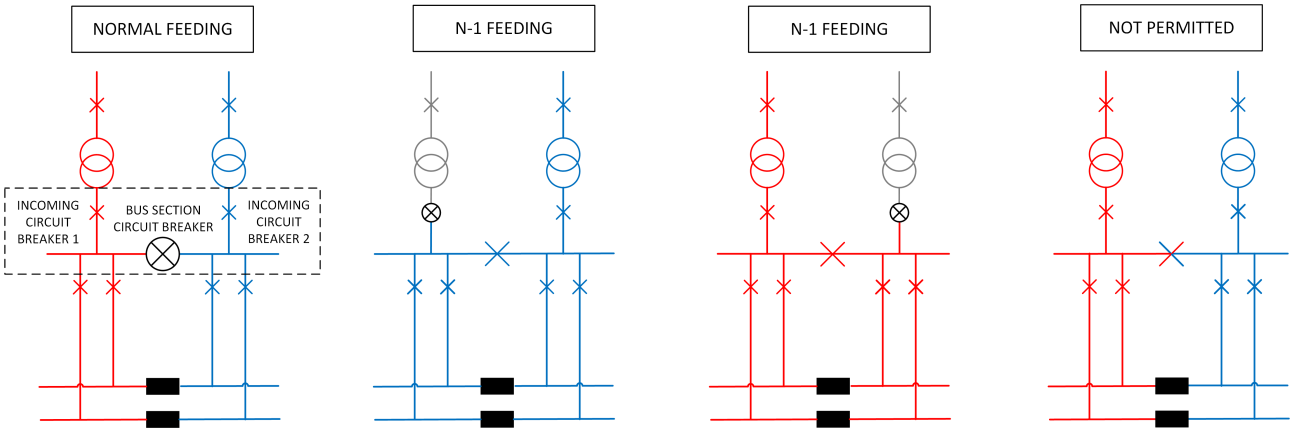


Figure 58: Two out of three interlocking; the first three scenarios are permitted, but the fourth is not

Additionally, the ESI disconnector cannot be operated without opening the railway incoming circuit breaker; this is achieved either by the physical transfer of a key between representatives of the two companies on site, or operation of an electrical interlock releasing the disconnector.

All of these systems are collectively designed to prevent connection of different grid supplies by ensuring switching is only carried out in a specific order, with disconnection of one circuit occurring before connection of the second one. Not all switches within the system are interlocked, but additional safeguards are provided by placing control of all switching under the ECO (section 10.7.3). Collectively these measures help provide safe and reliable operation of the power system.

10.8. Electrical Clearances

Since it is not possible to provide insulated conductors in an OLE system, it is essential for safety and reliable operation to keep all live OLE parts a sufficient distance from other infrastructure, so that *flashover* is prevented. For this reason two sets of air gap clearances are defined. The *static electrical clearance* is the clearance which must be achieved under permanent (static) conditions. The *passing electrical clearance* is a smaller clearance which must be maintained for a short duration as the train passes or another non-permanent event occurs.

This smaller clearance is justified by the lower risk level in a short-duration event.

These clearances are set for a particular system voltage, based on the *insulation coordination*[88] for the system. This involves selection of the right level of insulation strength to provide protection against both supply voltages and transient overvoltages, such as those experienced during lightning strikes[89]. The *lightning impulse withstand voltage* is typically an order of magnitude higher than the supply voltage, and is also the determining factor in the size of insulators (section 11.18).

It is usual to have several categories of static and passing clearance in recognition of the different circumstances which may apply. For instance, historically UK standards[90] defined four clearance categories;

- *Enhanced Clearances*, used wherever practicable;
- *Normal Clearances*, used where enhanced clearances cannot be attained;
- *Reduced Clearances*, only to be used with the consent of the infrastructure owner when normal clearances cannot be attained;
- *Special Reduced Clearances*, only to be used with the consent of the safety authority when reduced clearances cannot be attained.

The reduced level was introduced in 1962 based on operational experience and experimental findings; and the special reduced level was introduced in 1974 based on further testing and the introduction of a stress-graded bridge arm (section 11.10.9)[91].

The historical standards for the various voltage standards used in the UK prior to 2015 were as follows:

Voltage	Clearance	Enhanced	Normal	Reduced	Special Reduced
750V DC[92]	Static	≥75mm	75mm	N/A	N/A
	Passing	≥25mm	25mm	N/A	N/A
1500V DC[93]	Static	≥500mm	150 – 499mm	100mm	N/A
	Passing	≥500mm	≥100mm	99 – 80mm	N/A
25kV AC[94]	Static	≥600mm	270 - 599mm	269 – 200mm	199 – 150mm
	Passing	≥600mm	≥200mm	199 – 150mm	149 – 125mm

For AC systems this standard has been superseded by a new Group Standard[95] which introduces three levels of insulation; *reinforced insulation* (equivalent to the old enhanced level) provides the highest level of protection, *basic insulation* provides an acceptable level, and *functional insulation* (equivalent to the old normal level) provides a level which must be supported by a risk assessment. The old reduced and special reduced levels are

[88] Insulation coordination in European systems is specified in BS EN50124-1:2017 "Railway Applications – Insulation Coordination Part 1: Basic requirements - Clearances and Creepage Distances for all Electrical and Electronic Equipment"; 31 March 2017; BSI; section 5.2.

[89] A typical lightning withstand voltage for 25kV AC systems is 200kV. If an air gap or insulator breaks down under lightning strike conditions, the resulting arc will allow traction fault current to flow.

[90] GERT8025 "Electrical Protective Provisions for Electrified Lines"; Issue 1, October 2001; RSSB; section B4.6.2.

[91] "Railway Electrification: 25kV a.c. Design on B.R."; 1988; Director of Mechanical & Electrical Engineering, British Railways; section 4.2.

[92] HS(G)153/4 "Railway Safety Principles and Guidance, Part 2, Section C: Guidance on Electric Traction Systems"; 2005; HSE; section 43.

[93] Ibid.

[94] GERT8025 "Electrical Protective Provisions for Electrified Lines"; Issue 1, October 2001; RSSB; section B4.6.2.

[95] GLRT1210 "AC Energy Subsystem and Interfaces to Rolling Stock"; Issue 2, December 2019; RSSB; section 2.1.8.1 and table 5.

not formalised but remain available in extremis, subject to an appropriate risk assessment and implementation of mitigation measures.

Voltage	Clearance	Reinforced Insulation	Basic Insulation	Functional Insulation
25kV AC	Static	≥600mm	370 – 599mm	270 – 369mm
	Passing	≥200mm	≥200mm	≥200mm

Where reinforced insulation cannot be provided, such as at low overbridges, a section of contact wire typically replaces the catenary. This minimises the chance of wire *stranding* in the event of a flashover. This wire is known as *contenary*.

Figure 59: Catenary wire damage caused by electrical arcing. Rayleigh, UK

10.8.1. Voltage Controlled Clearances

It is possible to reduce air gap clearances further at overbridges by providing overvoltage protection by other means, reducing the air gap to a level sufficient to withstand the supply voltage. This can be achieved using a *Surge Diverter* (also known as a *Surge Arrester*). This device is a type of *Non-Linear Resistor*, and is connected between the OLE and traction earth at the OLE structure either side of an overbridge which requires small air gaps. At normal operating voltages it is an insulator and prevents current flowing to earth. However if the voltage in the system reaches the threshold (typically set at 300% of the supply voltage) the surge diverter becomes a conductor, allowing current to flow safely to earth rather than arcing across the air gaps in the system. A trip counter provides information on the number of overvoltage events, and a drop-out fuse link connected between the surge diverter and traction earth provides a visible disconnection in the event that surge current exceeds the capacity of the device.

Figure 60: Surge Diverter on trial; note drop-out fuse and actuation counter (arrowed). Glasgow, UK

This approach to reducing air gap clearances at overbridges is now in use in the UK[96], and has the potential to reduce the number of bridge reconstructions and/or track lowers (section 17.7) required for new electrification schemes. The resulting small air gap clearances are however vulnerable to being bridged by birds or debris, and additional measures are provided to prevent flashover in these circumstances. These include:

- Use of a bridge arm with a fully insulated head;
- Application of a special insulated coating to the length of the bridge soffit over each wire run;
- Application of an insulating plastic cover on the contact wire.

Air gaps using this combination of measures are known in the UK as *Voltage Controlled Clearances*, to differentiate them from clearances provided using conventional air gaps. It is possible to have passing clearance values as low as 20mm when using these measures, but their use requires careful design and a detailed risk assessment.

10.9. Safety Protection

The sliding contact function of OLE means that *protection by insulation* is not practical when it comes to protecting the public from the risk of electric shock. Instead *protection by separation*[97] is extensively used. This means maintaining minimum distances between places that people can access – *standing surfaces* – and all *live parts*. These safety separations are considerably larger than the electrical clearances for a given system. For instance, the minimum safety separation between a standing surface and fixed live parts[98] for 25kV AC lines in the UK was for many years 2.75 metres. This has now been increased to 3.5m.

[96] The first location in the UK to be permanently energised using surge diverters is at Cardiff Intersection Bridge, where constraints above and below the track made reconstruction or track lowering uneconomic.

[97] This type of protection is known in European standards as protection by clearance, but in this book "clearance" refers to air gap distances between two objects rather than between objects and people.

[98] In the UK the whole length of an insulator is considered to be live. Other administrations consider the limit of live parts to be halfway along the insulator. NR-L2-ELP-27715 "Overhead Contact System Design Specification Module 4: Electrical and Mechanical Clearances and Separation"; Issue 3, September 2018; Network Rail; section 6.1.2.

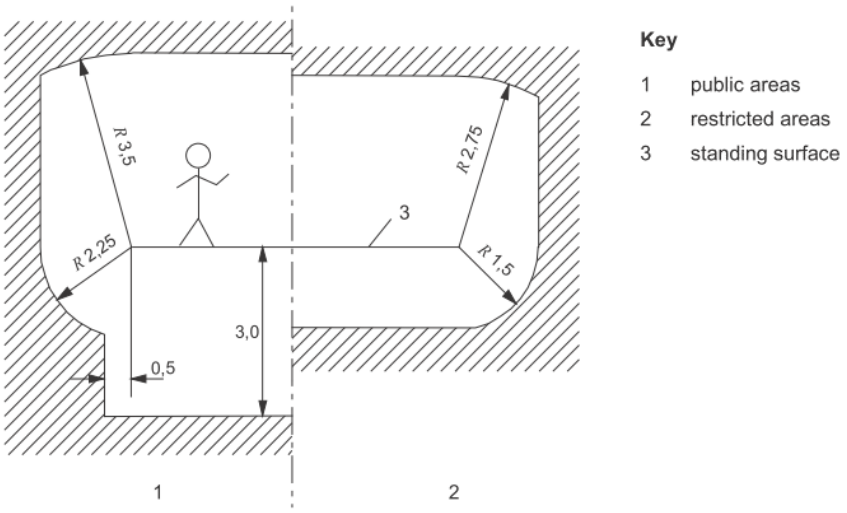


Figure 61: Minimum clearances to accessible live parts from standing surfaces[99]

Where it is not possible to provide protection by clearance, *protection by obstacle* is instead provided. The obstacle must meet predefined standards in terms of *ingress protection* and height[100], depending on where the standing surface is in relation to live parts. Solid floors are typically mandated for walkways over live parts to prevent objects or liquids coming into contact with the OLE.

For standing surfaces above OLE, such as overbridge parapets, an alternative to the fixed height approach is to specify a minimum *taut stringline distance* between the standing surface and live parts. This notional string line has one end placed on the standing surface, and is then pulled tight while being passed over the obstacle and toward the live parts.

It should be noted that the term "live parts" includes the pantograph itself. Due to the position and width of the pantograph, this can often be the most extreme part of the live envelope; it is important to consider this in the OLE design for both clearances and separations through overbridges, stations, signals and other infrastructure. In the UK pantograph live parts are only permitted to breach the 3.5m separation distance if a site-specific risk assessment has determined that the safety risks have been mitigated.

10.10. Earthing and Bonding

At its simplest, traction bonding provides the negative half of the traction circuit, with OLE providing the positive half. However, this in itself is not sufficient to provide a safe system. *Traction earthing and bonding* is the collective term used to describe a set of arrangements designed to:

- Provide a low impedance path for traction return current and fault current;
- Allow faults to be detected and cleared quickly;
- Keep the potential of exposed metalwork within safe limits[101];
- Eliminate touch potentials and step potentials.

[99] BS EN 50122-1:2011+A4:2017 Incorporating corrigenda November 2012 and May 2013 "Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 1: Protective provisions against electric shock"; 28 February 2017; BSI; figure 4.

[100] For instance European Standards permit the use of a vertical barrier with up to a 12mm^2 mesh for live parts alongside a standing surface in a restricted area, but mandate a solid wall up to a specific height for the same situation in a public area. Ibid.; section 5.3.

[101] For 25kV AC systems in Europe, the voltage of exposed metalwork should not exceed 60V for any period >300s, and not exceed 645V for more than 200ms. Ibid.; table 4.

Step potentials arise during fault conditions, or when current is allowed to flow to earth. During these conditions, the system earth electrode may be subject to a rise in potential. This will create a potential gradient in the surrounding ground, the potential reaching true earth or zero at some distance from the earth electrode. Step potential is the potential difference between a person's feet caused by this potential gradient.

Touch potentials arise where a metal service connected to another earth system (such as a level crossing barrier motor supplied from the DNO) is adjacent to OLE. In this situation, a person may be able to simultaneously touch the two earth systems (such as an OLE mast and an equipment cabinet). The two earths may be at different potentials, and so a current will flow through any person simultaneously touching both.

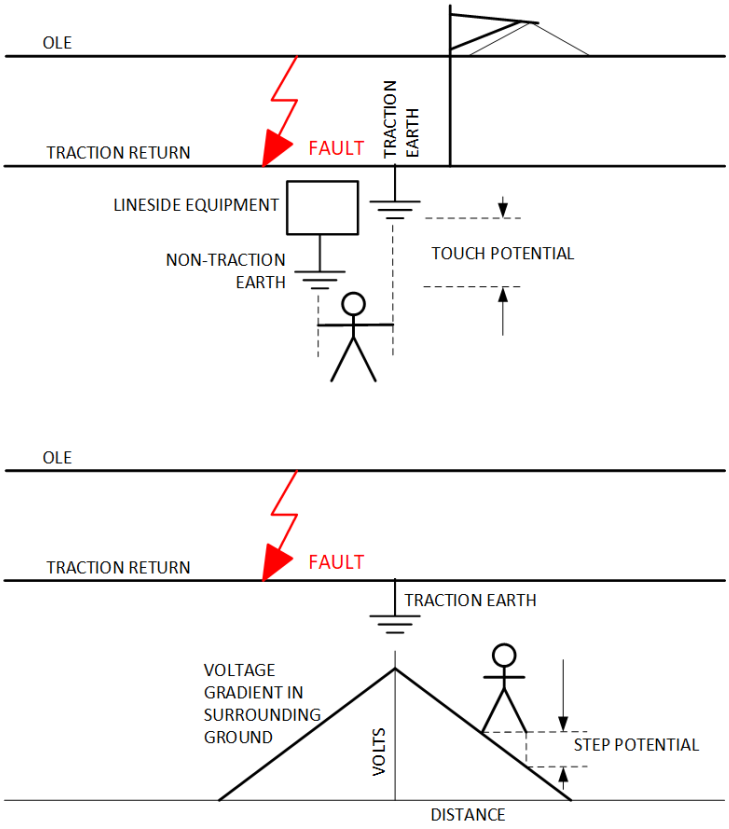


Figure 62: (top to bottom) Step and touch potentials

Both these situations give rise to unacceptable safety hazards, and so the earthing and bonding design must ensure these potentials are kept at acceptable levels.

10.10.1. AC Earthing and Bonding

AC systems are characterised by the creation of a distributed earth system using the general mass of earth; this is formed by using each OLE structure foundation as an earth connection. This system helps to keep the rail potential low in the event of a fault. The OLE structures are connected together by being bonded (along with earth wires) to the *traction return rail*, which may be one or both rails of each track (depending on the signalling system being used). This ensures that a fault on the structure will be cleared quickly. In electrical installation terms the earthing system is a *TN-C* type – that is, the *Circuit Protective Conductor* (CPC) and the *neutral conductor* functions are provided by a single shared set of conductors.

Figure 63: Structure to traction return rail bond. Harringay, UK

Other railway infrastructure is typically bonded to traction earth, to take account of the possibility that assets

which lie within the *Overhead Contact Line Zone* (OCLZ) and *Current Collection Zone* (CCZ)[102] may become energised under OLE mechanical failure conditions. These faults will create a safety risk if not cleared quickly – in particular, signal structures and metal bridges are usually bonded to traction return. Additionally, OLE can induce unsafe voltages in adjacent metalwork without direct contact, as described in section 10.10. This particularly affects long continuous lengths of connected metal such as lineside fencing.

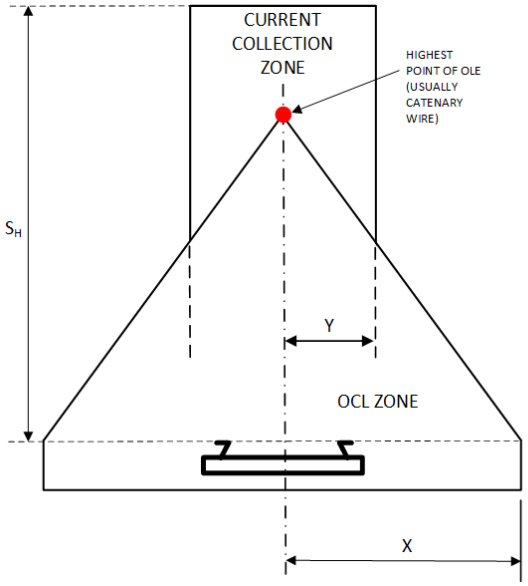


Figure 64: OCL Zone and Current Collection Zone[103]

For these reasons all exposed metalwork within the *equipotential zone* is generally bonded to traction earth, to ensure that no dangerous potentials can arise.

An important factor governing AC bonding design in mainline railways is that the main function of the rail is often not traction bonding. The primary purpose is the guiding of trains, but it is also used by those signalling systems which use *track circuits* to detect the presence of a train. For these systems the track is electrically sectioned by means of *Insulated Block Joints* (IBJs), also known as *Insulated Rail Joints* (IRJs). A voltage is placed across the rails at one end of the track circuit, and a relay detects the voltage at the other end. A train axle shorts the circuit, and this shorting is detected and allows the signalling system to locate a train. Track circuits have their own bonding system, and so the traction bonding must be integrated with the signalling bonding. Track circuits which use IBJs are known as *single rail track circuits*; where these are used, one rail of each track is designated the traction return rail - (although confusingly it also carries track circuit current and so would be better described as a common rail) and the other is reserved for signalling use only. *Double rail track circuits* (also known as *jointless track circuits*) eliminate the use of IBJs - which can pose reliability problems - by using high frequency AC voltages. For these types of track circuit both rails are used for signalling and traction currents, allowing the use of *double rail traction return*. Where no track circuits are present - in *axle counter* areas or sidings with no train detection - double rail traction return is also used.

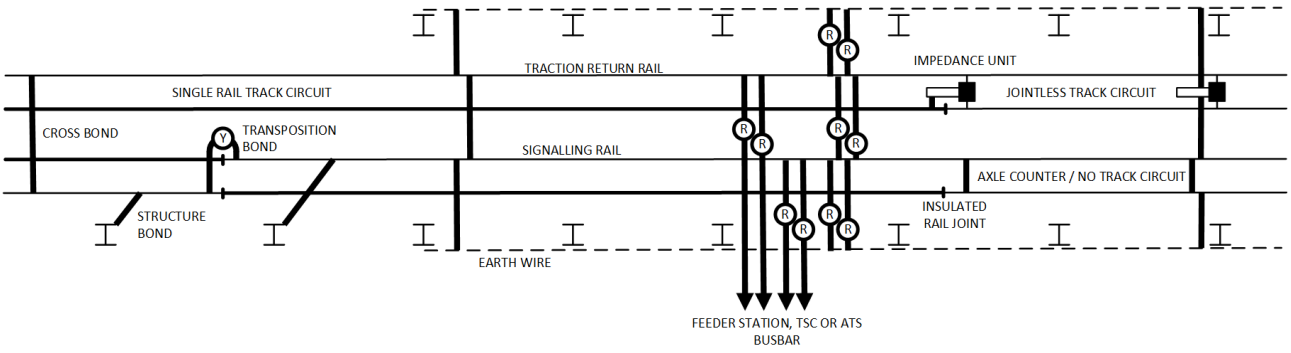


Figure 65: Typical traction bonding for various track circuit scenarios; note red and yellow bonds

[102] The OCLZ is the zone within which broken conductors may fall; the CCZ is the zone which a damaged pantograph may intrude into.

[103] Ibid., figure 1. In the UK S_H is defined as 6.8m, Y is defined as 1.4m, and X is defined as the lesser of 5.2m or the distance to the OLE structure. GLRT1210 "AC Energy Subsystem and Interfaces to Rolling Stock"; Issue 2, December 2019; RSSB; section 3.2.1.1.

AC railways use the traction return rails to form the core of the AC bonding system, and are typically configured to provide a path to earth of less than 1Ω impedance – this is known as *traction earth*. All of the conductors in the circuit – both live and earth – play a part in setting this impedance, so any significant change to the OLE configuration will also have an impact on impedance and therefore protection settings (section 10.7.1).

Figure 66: Continuity bonds across expansion joints. Tynemouth, UK

Bond connections are typically made using PVC-sheathed aluminium cable (section 11.16.5). Connections to the traction return rail use a crimped lug, which connects to a through-bolt in the web of the rail; a special compression bushing is fitted into the drilled hole, to maintain the strength of the rail, protect against the formation of cracks and provide a flat face for a good electrical connection.

The physical configuration of the bonding system is based on a set of simple principles.

Traction rail continuity must be provided at all locations, so that any train has a minimum of two paths for traction return current to flow; direct to the supply point, and in the opposite direction to the nearest cross bond location, and then back via another path. This is guaranteed by placing *continuity bonds* across any interruption in the traction return rail, such as *expansion joints* (where a gap in the rails is provided for thermal expansion).

Continuity must also be ensured where the traction return rail swaps sides, a situation frequently required in track circuited railways. In this case a *transposition bond* is placed across the IBJs which form the transposition point.

Transposition bonds are also a necessary feature at turnouts in track circuited systems, where IBJs are necessary to prevent the turnout geometry from shorting out the two rails.

Low impedance is essential, and is attained by bonding the traction return rails together at frequent intervals. For instance, in the UK AC railways are provided with *cross bonds* which connect all traction return rails (and any earth wires), typically every 400m. These locations are coincident with DEPs (section 10.12) to provide a secure path to earth in the event of inadvertent re-energisation during an isolation.

Figure 67: Transposition bond across IBJs (arrowed). Stratford, UK

Impedance is further reduced by connecting all of the OLE structures to the traction return rail, either directly or via an aerial earth wire. This provides two important features: firstly the foundations form a distributed earth farm, tying the whole system to earth potential; and secondly, it provides a direct connection for fault current in the event of an insulator or similar failure at a structure.

Jointless track circuits are prone to interference from traction fault current, so OLE systems which are co-located

with this type of track circuit are provided with an OLE *earth wire*. This is connected to the traction return rail at cross bond locations by means of an *impedance unit*, which is a low-pass electrical filter that allows traction current to pass while blocking the track circuit frequency.

Figure 68: Cross bonding on axle counter railway. Newbury, UK

These are also provided at transposition bond locations and the interface between jointless and conventional track circuits. The OLE structures are then bonded to the earth wire rather than direct to the traction return rail. The earth wire may be buried, but is usually aerially suspended between structures for security.

Bonds are also provided at all feeding and sectioning points to connect the traction return rails and the *neutral busbar* at the feeder station, ATS or TSC. This forms the main path for traction return current to leave the rails, and as such these cables can give rise to dangerous voltages if disconnected. For this reason in the UK they are designated and marked as *red bonds*, meaning they should not be disconnected without an isolation.

Some bonds have a dual function, providing both traction continuity and track circuit continuity. These bonds are designated *yellow bonds* in the UK and marked as such.

All of these ground-level bonds are vulnerable to damage from track maintenance *tamper vehicles*, and regular inspections are required. In the UK *spider plates* are increasingly used to allow easy cable replacement.

These features collectively provide the backbone of traction bonding of any AC electrified railway. However this in itself does not provide a safe system since a large number of other assets and systems must also be protected by being bonded to traction earth. These include:

- Overbridges and underbridges;
- Station ironwork and metal canopies;
- Signalling structures;
- Level crossing barriers;
- CCTV and radio masts;
- LV power supplies for signalling, points heating, stations and level crossings;
- Metallic fencing;
- Crash barriers;
- Metal bridge parapets;
- Any other substantial exposed metalwork.

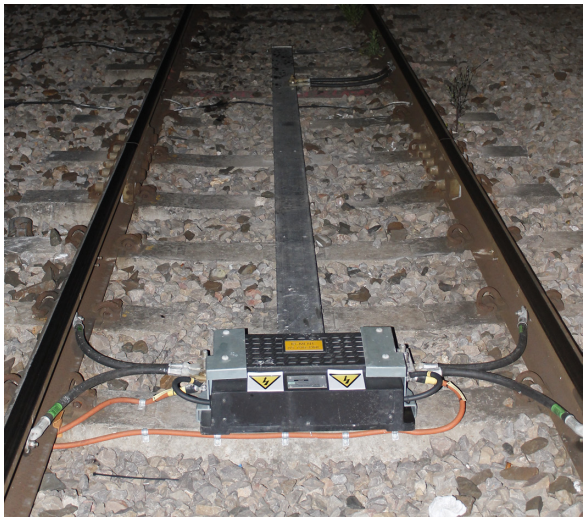


Figure 69: Impedance unit forming transposition bond in TI21/EBI200 jointless track circuit. Didcot, UK

Figure 70: Red bonds at a spider plate connecting a TSL to running rails. Acton, UK

However it is often not desirable to connect LV equipment to traction return. For instance, LV equipment connected to a DNO earth will not tolerate large OLE fault currents; additionally, the two earth systems may be at different potentials, allowing current to flow between them.

In this case, it is important to locate this equipment away from the OCLZ and a sufficient distance from traction bonded equipment that touch potentials may not arise. If this is not possible, an insulating shroud or earth gapping may be required instead.

Bonding at stations requires special care, since LV systems bonded to traction earth may experience current levels during fault conditions which their CPCs are not sized to cope with. Segregation of HV and LV is often not practical, with OLE structures and LV-connected services in close proximity; in which case the LV earth system will be bonded to traction earth via a *green bond* at one controlled point, with or without LV earth gapping elsewhere.

Long metallic assets running parallel to the OLE - such as fences and metal pipes - are typically gapped or provided with a non-metallic section every 200m to prevent induced voltages (section 10.4) from reaching hazardous levels.

Overline structures often have small electrical clearances (section 10.8) and so require special measures to mitigate the increased risk of flashover. In the UK non-metallic bridges with electrical clearances of less than Reinforced Insulation level are provided with *Conductive Assemblies* (also known as *Flashover Strips*). These copper strips are placed on the bridge underside in line with the OLE and bonded to traction earth. Any flashover will generally migrate to the conductive assembly as the lowest impedance path, resulting in the fault being detected and protecting the vulnerable concrete from arcing damage. Metallic bridges are bonded direct to traction earth and so do not need flashover strips.

Figure 71: Structural reinforcing bonded to aerial earth wire. Farringdon, UK

For those items which are to be bonded to traction earth, the choice over the bonding configuration depends on the specifics of the system and administration preferences. Some administrations choose to *nodal bond* these items to traction return. This ensures that all fault current will flow along a well-defined single path to earth.

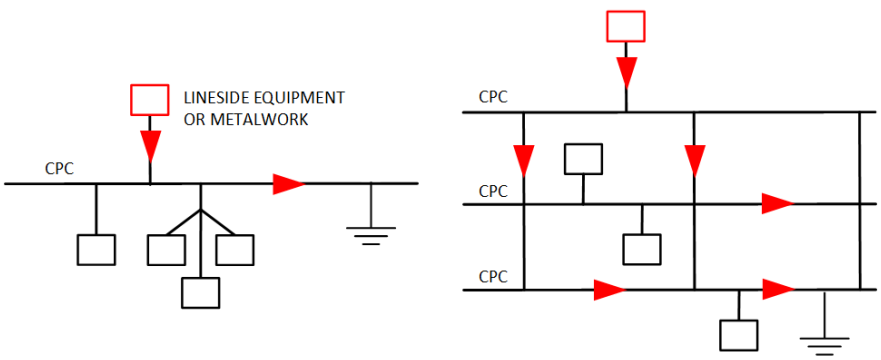


Figure 72: (l-r) Nodal bonding and mesh bonding architectures, showing fault current flows

Figure 73: Non-metallic fitted bridge with insulated head bridge arms and conductive assemblies (arrowed). Newbury, UK

Figure 74: Concrete burns and spalling damage from arcing at a bridge. Stowe Hill, UK

Alternatively the systems can be *mesh bonded*, providing multiple paths for fault current to flow. This has the advantage of reducing the fault impedance when compared to nodal bonding, but there is naturally less control over how much current flows in particular paths. Mesh bonding is particularly useful in stations, where it can be difficult to separate traction and LV return systems.

Sometimes structures need protection from AC traction current. In this case, *secondary insulation* may be used. This is an additional level of insulation inserted between the primary insulation and the mass of earth. A connection to traction return is made between the two sets of insulation, and this captures any fault current, preventing it reaching the general mass of earth.

This method is used to provide an additional level of protection against flashovers – for instance, at sensitive overbridge locations or heritage structures where AC stray currents are to be avoided.

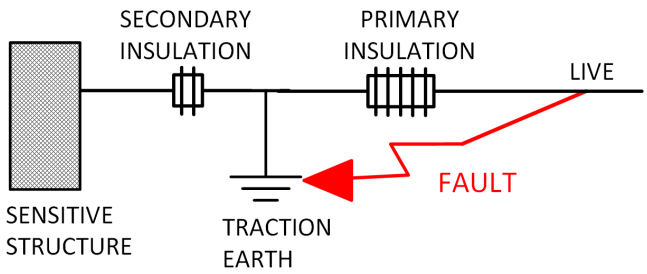


Figure 75: Principle of secondary insulation

Special measures are required at the limits of electrified railways, to protect the adjacent non-electrified lines. This typically takes the form of single or double IBJs in all rails, to block any traction current from leaving the system. Similar precautions are also are needed at locations where flammable substances may be present, such as at oil or gas loading depots. It is often not safe to directly bond oil or gas pipes passing over the railway or to extend the equipotential zone to cover them, due to the risk of traction current flowing into the pipe.

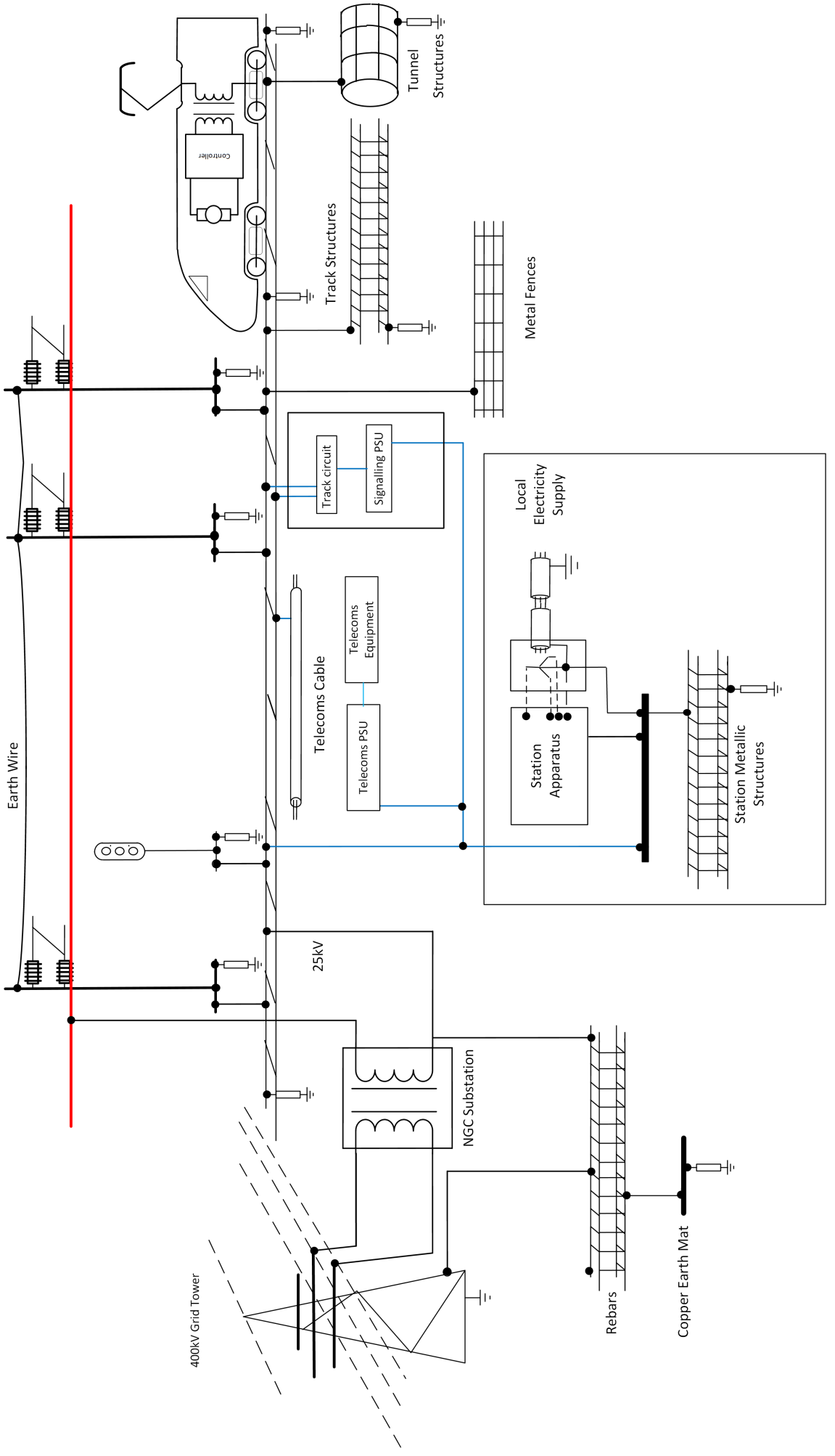


Figure 76: Bond connections for a typical mesh-bonded railway

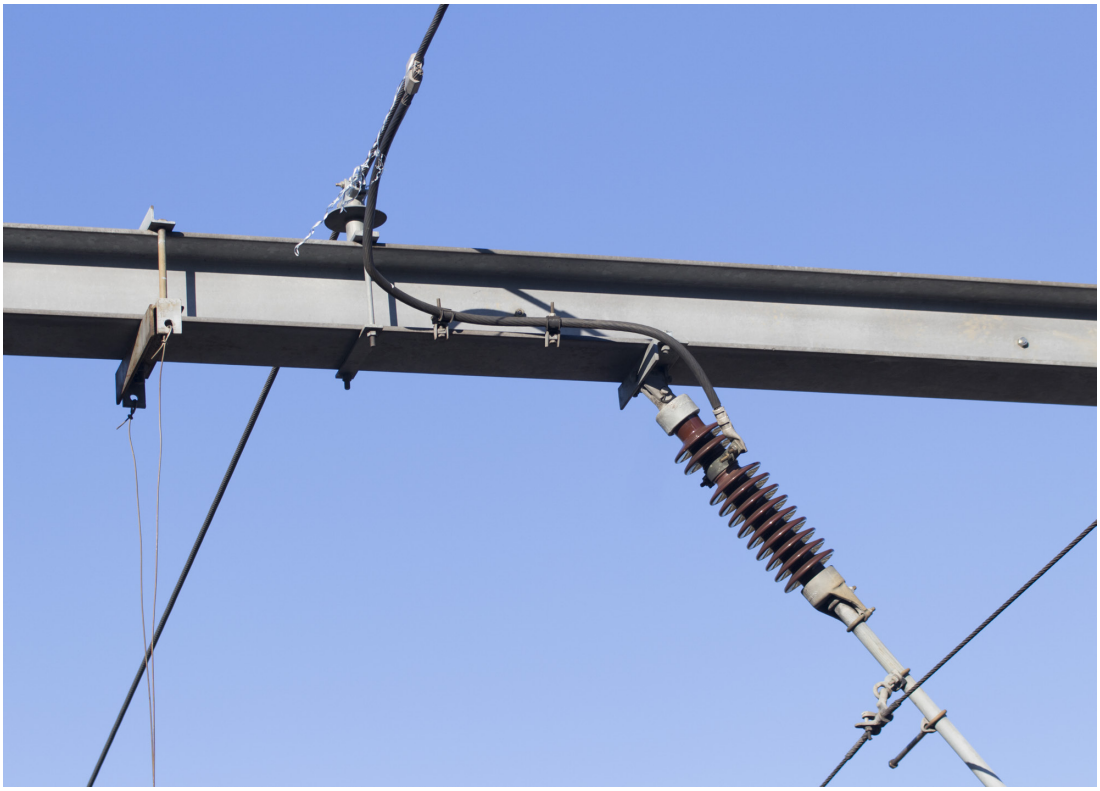


Figure 77: Secondary insulation protecting a sensitive viaduct; note connection to earth wire (which is insulated from the structure). Kentish Town, UK

10.10.2. DC Bonding and Stray Currents

Earthing and bonding principles for DC systems differ than those for AC systems. This is because *DC stray currents* can be especially damaging to the running rails, as well as to metal services and foundation reinforcement – because of the phenomenon of *cathodic corrosion* (also known as *galvanic corrosion*). This occurs when current flows continuously between dissimilar materials – for instance from a metal into adjoining soil. The metal is corroded, eventually to such an extent that a hole may appear – a particular issue with metal services adjacent to the DC supply point. The volt drop within the traction return system means that current will naturally flow from the rails to surrounding ground near the train, and back into the rails near the supply. Any metalwork in the path of these flows - such as masts, foundations, bridge metalwork, reinforcing bars, water and gas pipes - are vulnerable to damage.

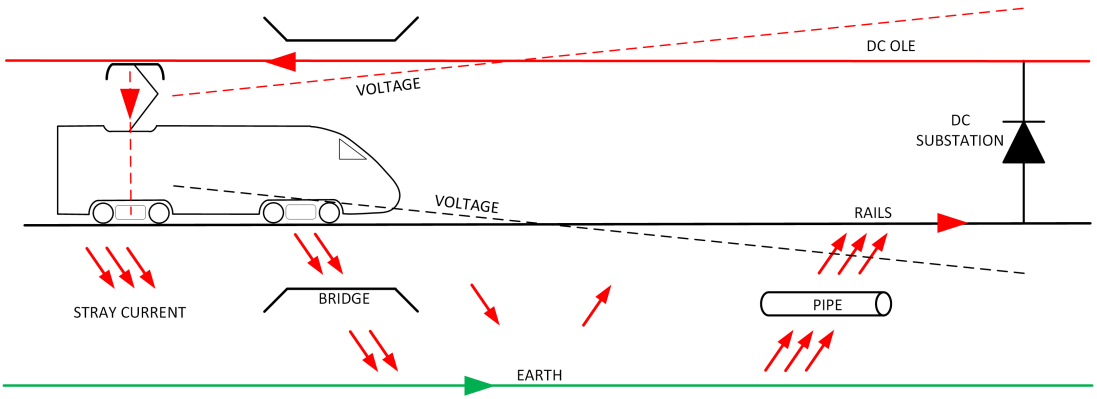


Figure 78: DC stray current flows in a DC OLE system without mitigation

These problems mean that on DC OLE the earthing system is entirely different to that of AC systems. The entire OLE system is insulated from the general mass of earth, so that stray currents cannot leave the system.

DC tram systems typically use two levels of OLE insulation – *double insulation*[104] – to protect people from electric shock and street-level assets from the effects of stray currents. OLE structures are not bonded to rails and so are protected from corrosion.

Figure 79: (l-r) Foundation damage due to effects of stray currents on reinforcing bars, and replacement with secondary insulation to prevent DC current flowing into foundation (arrowed). North London, UK

The lack of a system earth can lead to unacceptable voltages between the rails and exposed metalwork under high train load or fault conditions, and some systems counteract this by installing *short circuit devices* at stations to temporarily disconnect the supply[105].

Figure 80: Double insulation (red insulators and top tie parafil rope) on tram cantilever. Manchester, UK

The question of how to insulate the return half of the circuit (the track) is more problematic; for a variety of reasons there is no one standard approach to this problem, but the available solutions can be grouped into three categories.[106]

[104] BS EN50122-2:2010 incorporating corrigenda February 2011 and March 2011 "Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 2: Provisions against the effects of stray currents caused by d.c. traction systems"; 31 March 2011; BSI.

[105] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p68.

[106] "Stray Current Control – An Overview of Options" , N. Dekker; 1999; IEE; Section 1.

The first option – *fully insulated earthing* – provides insulation immediately below the rails, and bonds the rails to local earth at each substation. Thus the rails are intended to be the only path for return current. Maintenance of the rail insulation is essential to successful operation of this system.

In railways with a reinforced concrete trackbed, this system is often provided with a form of secondary protection – a *stray current collection* mat – in case of failure of the rail insulation. The steel reinforcing bars within the top layer of the trackbed are tied together to maximise its conductivity relative to the conductivity of those to ground. An additional parallel return cable may be bonded to the reinforcing bars to reduce resistance further.

There is some debate as to whether this secondary measure is effective at limiting stray current leakage. Older installations included a diode between the stray current collector and the substation earth, but this was found to cause much higher secondary stray currents to flow, resulting in high levels of corrosion at the rail. As a result the use of diodes in this way is now deprecated in European Standards[107].

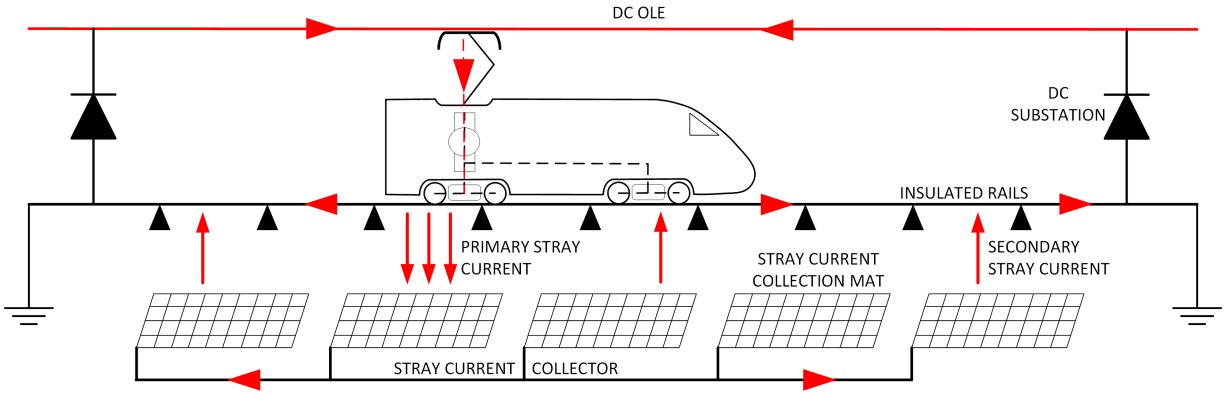


Figure 81: Fully insulated earthing and stray current collection mats on DC OLE

The second option – which is now being installed in many tram and metro systems – keeps the rails insulated and connected to the rectifier , but removes the earth connection at the substation, resulting in a *floating return*. Theoretically this reduces the likelihood of earth leakage since no direct path to the substation is provided for stray current, but the disadvantage is that any stray current that does reach ground is no longer under control. Many systems use this in conjunction with a stray current collection mat.

The final option – one which has been widely adopted by historic DC systems – is to have no specific control measures at all. Any rail insulation exists purely to reduce vibration and sleeper damage, and the electrical insulation properties are incidental. Some railways, such as the DC lines between London Euston and Watford, are able to operate satisfactorily in this way due to the geography and specifics of the feeding system[108], while others will experience ongoing corrosion problems due to the absence of mitigation methods.

10.11. Dual Voltage Areas

There are many locations where AC and DC electric railways meet, including:

- AC and DC systems coming into proximity at a complex location, such as a tram-train interchange;
- Separate AC and DC railways running in parallel on a transport corridor or at a station;

[107] BS EN50122-2:2010 incorporating corrigenda February 2011 and March 2011 "Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 2: Provisions against the effects of stray currents caused by d.c. traction systems"; 31 March 2011; BSI; section 8.

[108] "Stray Direct Current – a View from the Main Line", F. Waterland; 1999; IEE; section 2.

- Separate AC and DC railways crossing, either at grade, overline or underline;
- Voltage conversion within a single railway, with trains switching from AC to DC and vice versa at a voltage switching location;
- A single railway carrying both AC and DC electrification in parallel – usually meaning AC OLE and DC 3rd or 4th rail.

Figure 82: 25kV AC/750V DC changeover. Drayton Park, UK

We have seen that the bonding arrangements for AC and DC electrification are in opposition to each other, and this poses special problems whenever the systems meet. While in theory each system can affect the other in undesirable ways, in practice – and often depending on the standards applied when the first system was built – one system can usually be considered the cause and the other the victim[109]. The level of interference is largely determined by the configuration of the traction systems involved, which adds another level of complexity[110]. AC systems will produce interference via inductive coupling, and to a much lesser extent can also interfere via *capacitive coupling*; meanwhile DC systems will typically export cathodic corrosion to surrounding systems. Problems can multiply when the signalling systems of the respective systems are included – immunisation against AC being no protection against DC, and vice versa.

[109] "Consequences of DC Components in AC Railway and their Elimination", Midya, Thottappillil, Schütte; 2007; Uppsala University.

[110] "Stray Direct Current – a View from the Main Line", F. Waterland; 1999; IEE.

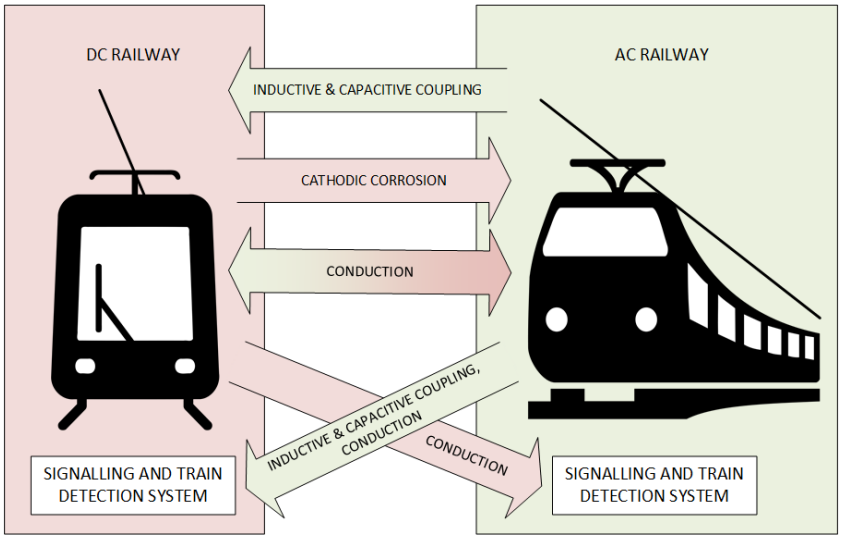


Figure 83: Causes and victims of interference at AC-DC interfaces

The particular geometries of the interaction play a part in determining the effects, and make modelling of the problem much harder. There is no single perfect solution to the interaction of AC and DC systems – each situation must be assessed and modelled, and an appropriate solution found[111]. All of the available solutions involve compromises, and are best described as controlling the problem, rather than eliminating it. It is much harder to design immunisation problems out of a system after it is built, and so wherever possible the solutions should be incorporated during the original construction.

A full description of the potential solutions is beyond the scope of this book, but the following sections describe solutions which have been used to greater or lesser effect, and their respective advantages and disadvantages. A list of UK locations with dual voltage electrification, and their mitigation measures, can be found in Appendix B.

10.11.1. DC Transition - Isolating Section in AC

This solution is relevant at a transition between an AC and a DC system on a single set of tracks. Here the requirement is to permit changeover from AC to DC and vice versa, allowing for continuous operation of trains, while protecting vulnerable lineside LV systems and OLE structures from the effects of stray currents. IBJs (section 10.10.1) are used to prevent the flow of DC current from the rails into an AC area, or vice versa. It is necessary to provide two sets of IBJs, sufficiently far apart that the longest train (electric or otherwise) cannot bridge both sets; otherwise each train would connect AC and DC areas together, and undesirable currents would flow through the train body.[112]

However this arrangement still requires a means to be provided for traction current to return from an electric train to the power supply. The means of doing this depends on the specifics of the interfacing electrification systems.

[111] BS EN50122-3:2010 incorporating corrigenda February 2011 and March 2011 "Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 3: Mutual Interaction of a.c. and d.c. traction systems"; 31 March 2011; BSI; section 4.1.

[112] Ibid.; appendix A.

Figure 84: Isolating transformers at boundary of 3rd rail DC and overhead AC area. Acton, UK

The first option places the isolating section in the AC-only railway. Section insulators (section 11.6.1) are placed directly over the IBJs, and isolating transformers (section 10.2.4) are used to transmit power to an AC train beyond the IBJs. The OLE earth wire is segregated and all OLE structures bonded to the adjacent earth wire section. The system is analogous to an airlock, allowing continuity of AC traction current to the train but blocking DC current, which cannot flow across the transformer interface.

The following diagrams depict transfer from an AC OLE system to a DC conductor rail system, but these methods can equally be applied to AC OLE to DC OLE transfer, when combined with a suitable neutral section (section 11.6.3).

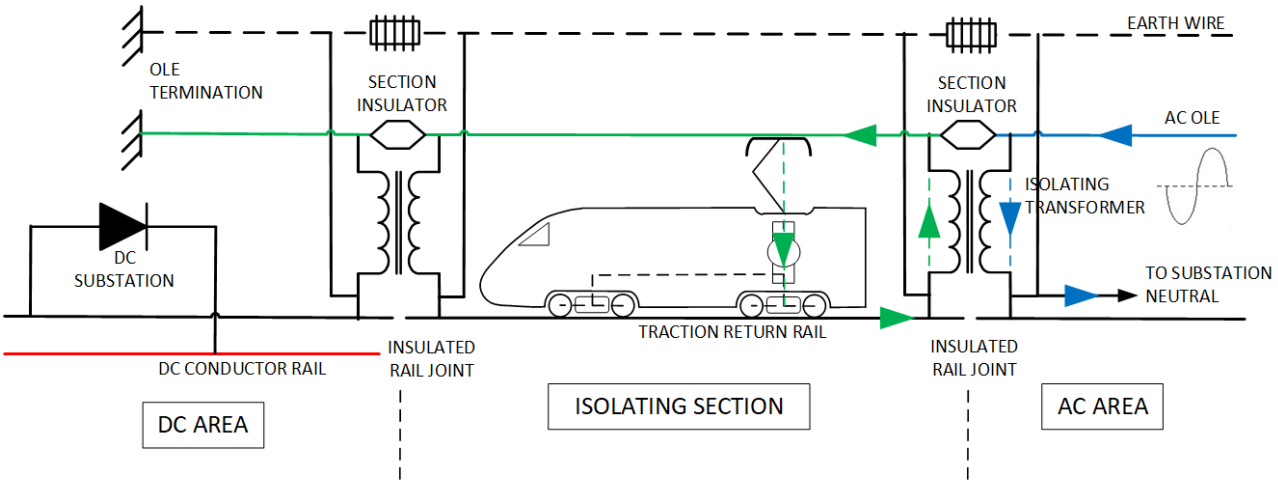


Figure 85: Isolating transformers used for AC/DC isolating section

This option has the advantage of being simple, with no moving parts or control system required. However care is needed in the design of earthing and bonding to ensure than the OLE structures and bonding does not provide a path for current to bypass the isolating transformer. For this reason, complex track layouts, station areas and overbridge locations are best avoided.

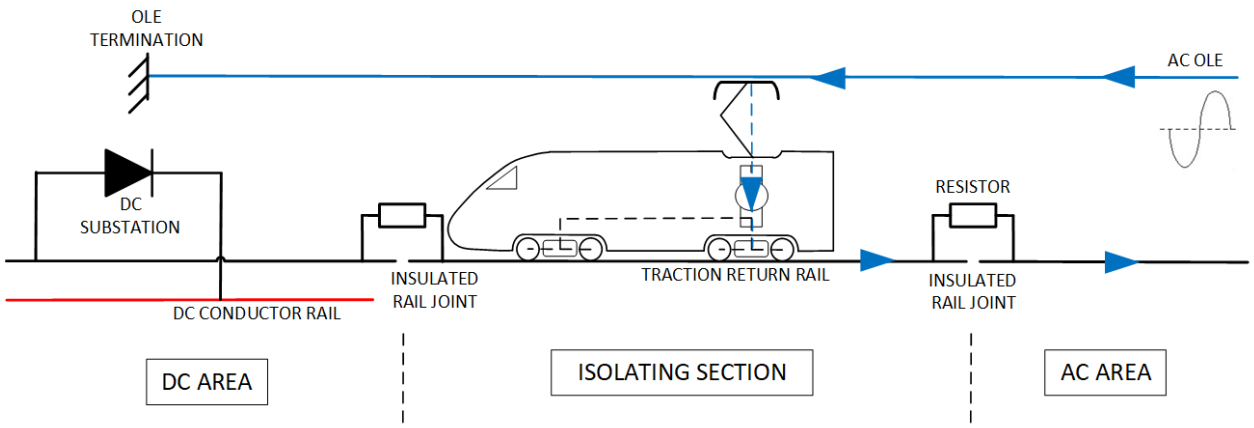


Figure 86: Resistors used for AC/DC isolating section

A simplified version of this configuration removes the section insulators and provides continuous OLE into the isolating section, and then connects resistors across the IBJs, with a resistance value that ensures the volt drop does not cause electric shock risk or damage to trains. This reduces stray currents rather than eliminating them, but can work if DC voltages, AC traction currents and AC fault currents are all low.

A further variation replaces the resistors with *bandpass filters* – consisting of capacitors and inductors – which block DC current but allow the AC traction frequency current to flow unimpeded. Spark gaps (section 10.11.3) are provided to protect the capacitors in the event of a short circuit. This solution needs very careful design, since ageing of the filters, harmonics and over-voltages can all damage the equipment or cause unsafe voltages to arise.

10.11.2. DC Transition - Isolating Section in DC

Alternatively, where an AC OLE railway interfaces with DC conductor rail, the isolating section can be placed in the DC system. The two sets of IBJs are retained, and the conductor rails are gapped coincident with the IBJs. DC *contactors* are used to temporarily bypass the gaps and IBJs when trains are passing. The contactor operation is triggered by the train detection system, and is configured so that the contactors at each end of the isolating section are never closed simultaneously. It thus provides a similar airlock approach to that of section 10.11.1, but by mechanical rather than electrical means.

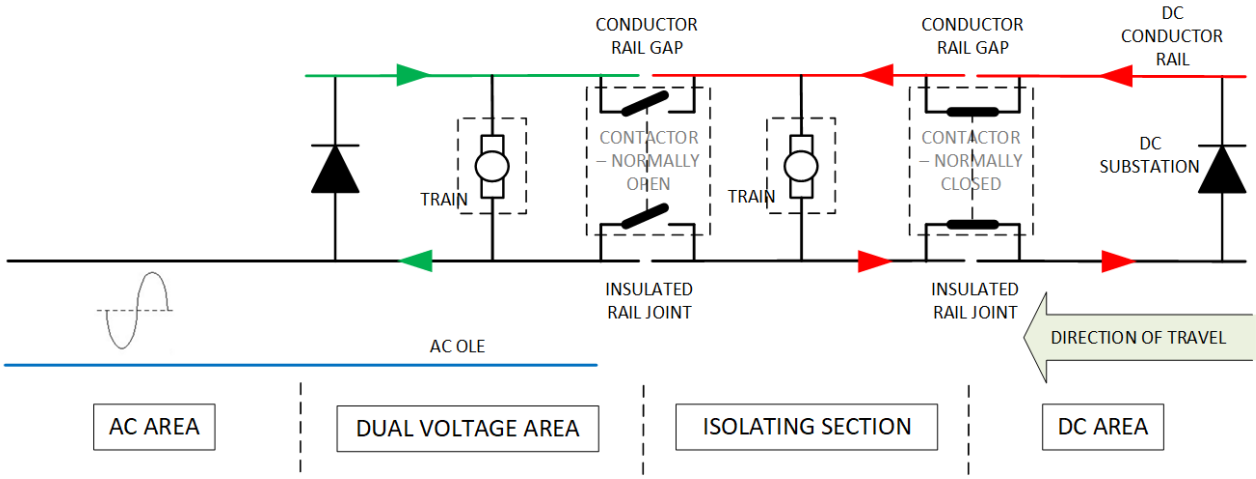


Figure 87: DC contactors used for AC/DC isolating section

This system is effective, but adds complexity and significant maintenance of the contactors and control equipment. Stray current monitoring is typically provided for this configuration.

10.11.3. Shared AC and DC Lines

Lines which are provided with both AC and DC electrification on a single set of tracks – usually AC OLE and DC 3rd or 4th rail – present a particular problem since the segregation methods outlined in previous sections cannot be used. The principles of AC bonding (section 10.10.1) are completely at odds with normal provisions to prevent DC stray currents from flowing in other metallic systems, whether it be the OLE itself, an LV station supply or a steel bridge.

Figure 88: Soulay Spark Gap. Monkseaton, UK

A number of different approaches are available, which may be more or less effective depending on the specifics of the situation.

The first option is to maintain AC bonding principles as per section 10.10.1, with special measures taken to limit the magnitude of DC stray currents. This could include a DC substation which only feeds the dual voltage area, with conductor rails and running rails isolated from the remaining railway; reducing the volt drop in the DC return circuit, using parallel return cables or additional rails in the return circuit to reduce the resistance; and bonding railway metalwork such as station and bridge metalwork to traction return as close to the DC substation as possible.

Alternatively, AC bonding principles can be maintained as per section 10.10.1, with special measures taken to limit the impact of DC stray currents. This could include reinforcement of bonding conductors and earth wires; a specially-designed DC substation at the AC/DC changeover point to keep DC rail voltage at zero or a negative value; and segregation of earths of third party assets from the rails.

Finally, devices such as *spark gaps* or non-linear resistors can be placed between bridge and station metalwork and the traction earth; these prevent DC from flowing into the asset, but allow AC fault current to flow across the device. These devices are not trouble-free; spark gaps can weld themselves closed, and non-linear resistors are hard to use in high fault current situations.

10.12. Earthing for Construction and Maintenance

10.12.1. Temporary Earthing Arrangements

Temporary earths are required to protect staff against *inadvertent re-energisation* and induced voltages (section 10.4) during construction and maintenance activities on or near to the OLE. The primary level of protection is provided by one or more Circuit Main Earths (CMEs); these are connections between the OLE and traction earth at each location on the circuit where inadvertent re-energisation could occur as a result of human error (such as reclosing a circuit breaker or misrouting an electric train into the section). The function of a CME can be provided either using portable earth cables, or via an earthing isolator (section 11.7.1). In the former case *earthing stalks* and/or *line guards* are provided on the OLE for these connections.

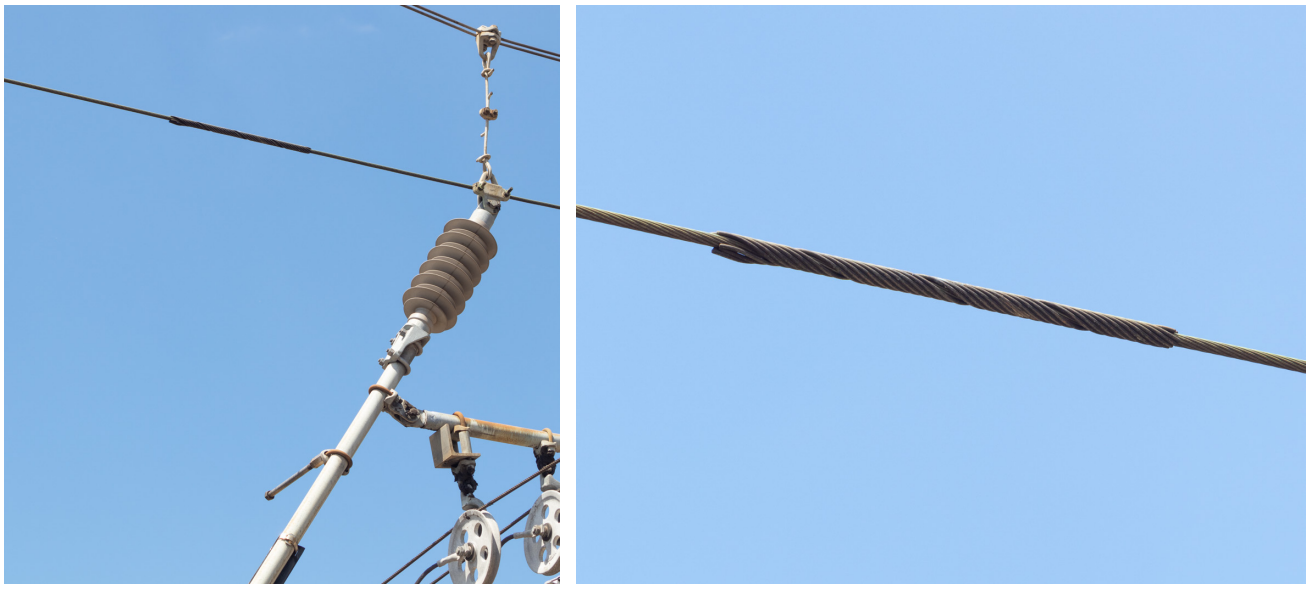


Figure 89: (l-r) Live side DEP stalk and earth side line guard, detail on line guard. Ealing, UK

A section of OLE being protected by CMEs at either end may be sufficiently long that induced voltages could lead to hazardous touch potentials. For this reason *Designated Earth Points* (DEPs) are also provided every 400m between the CMEs. These can also be provided by means of earthing isolators, but are more commonly provided for with portable earths.

In the UK, construction earths (blue) are differentiated from maintenance earths (orange).

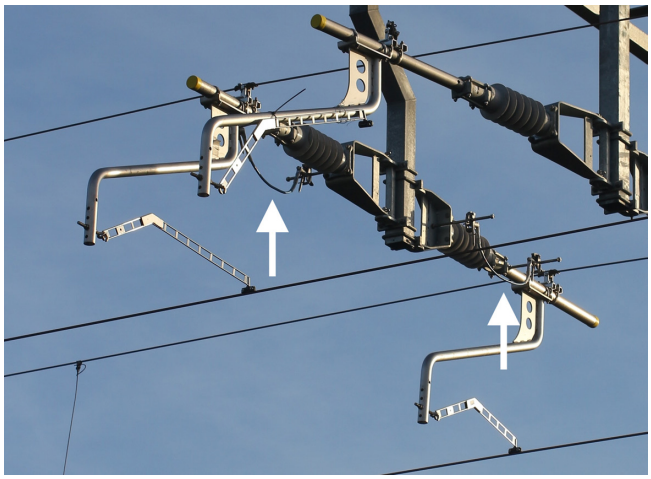


Figure 90: Designated Earth Point with blue portable construction earths (arrowed) applied

10.12.2. Buffer Sections and Permanent Earths

It is often necessary, for the protection of staff during a longer period of OLE construction works, to permanently earth a section of OLE using a *Permanently Earthed Section* (PES).

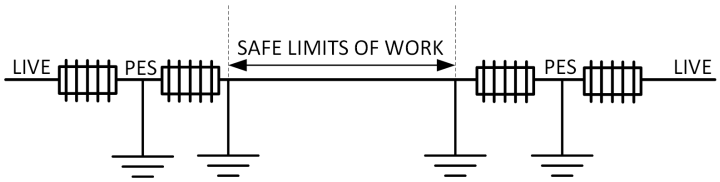


Figure 91: Principles of permanent earthing and buffer sections

This is done by isolating the section of OLE from the live sections around it, and installing permanent earths at the limits of the section. Construction earths close to the start of the PES then form the *safe limits of work* for construction staff.

Figure 92: Permanent earthing connections. Newbury, UK

11. Mechanical Principles

11.1. The Pantograph

The key interface to be considered in OLE design is that of the contact wire and *pantograph* (or *pan*). It is the pantograph which collects traction current from the OLE, and it is so-called because of the parallel linkage used to maintain a level pantograph head.

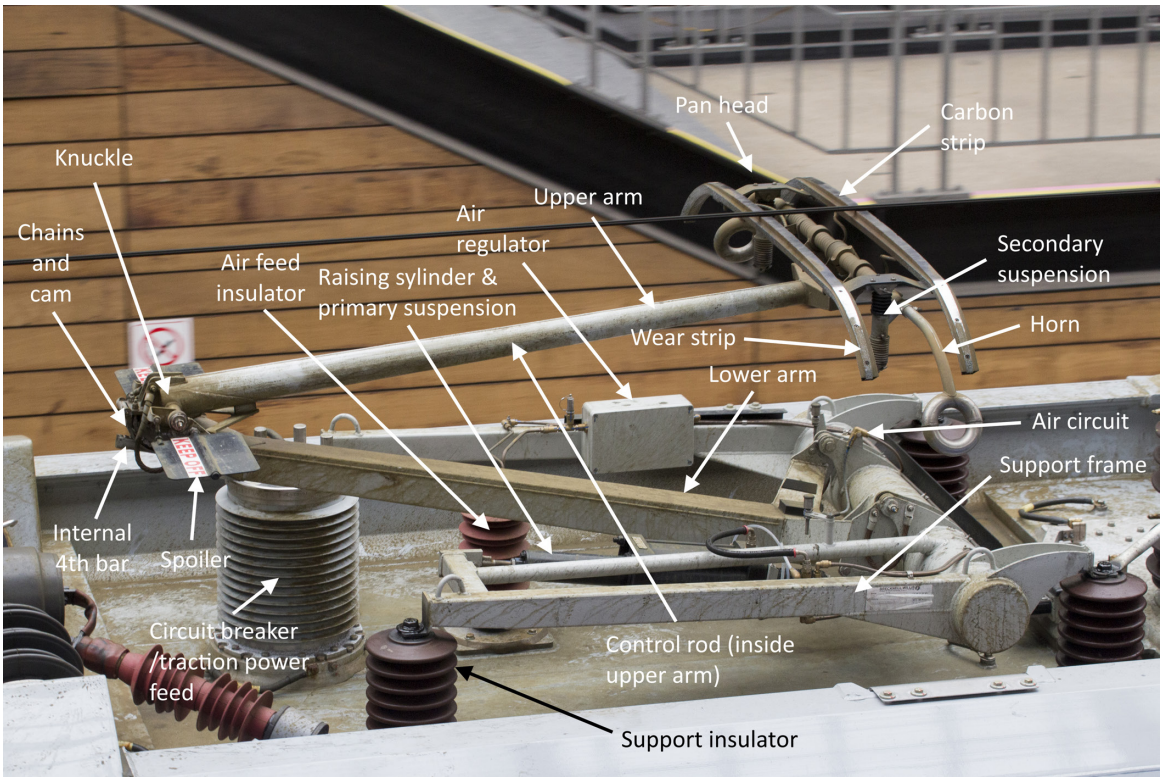


Figure 93: Typical mainline pantograph

This linkage ensures the head is always parallel with the contact wire. The pantograph is maintained on the wire by an upward force generated by an actuator (which is generally a pneumatic cylinder, although historically has been a mechanical spring). This raises the lower arm, and the upper arm is raised either by an external bar linkage, or by an internal *4th bar* which pulls a set of chains around a cam at the *knuckle*. This approach has the advantage of minimising aerodynamic disturbance from external links. The actuator also acts as the *primary suspension* for the system. *Secondary suspension* is usually provided on pantograph heads designed for mainline railways, and some high speed pans provide *tertiary suspension*. Secondary and tertiary suspension can be provided by a variety of means, from torsion bars to radial arms or plunger springs.

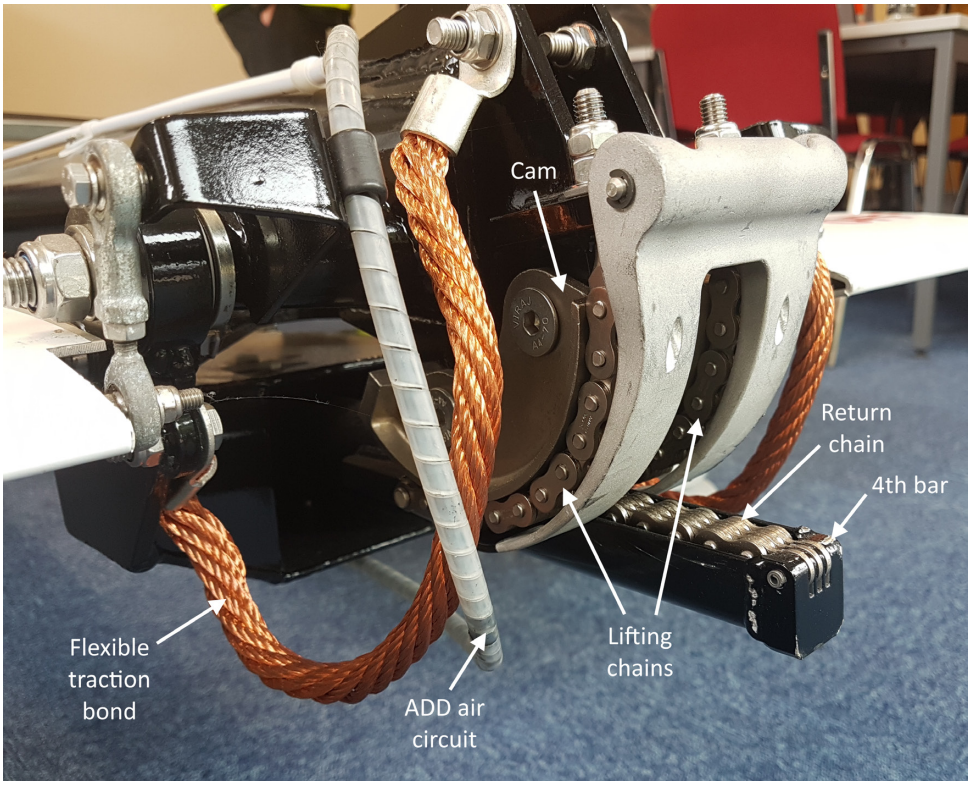


Figure 94: Brecknell Willis pantograph knuckle

The head itself is designed to be of low mass to reduce inertia, and typically supports one or more rows of *carbon strips*[113]; these form the interface with the contact wire. Carbon is used because it has good electrical and thermal conductivity, is self-lubricating, and has a much lower hardness than the contact wire. This means that most of the frictional wear is taken by the carbon strips rather than the OLE (it being far easier and cheaper to replace the carbons than the contact wire). Many administrations, including the UK, impregnate the carbons with copper (and historically, lead) flakes to improve its conductivity. In the UK up to 35% impregnation by weight is permitted.[114] A set of carbon strips will typically last 80,000km before needing replacement.

The dynamic performance of the pantograph is partly a function of the *unsprung mass* of the elements between the secondary (or tertiary) suspension and the contact wire; the lower the mass, the better the ability to absorb small changes in contact wire position. Modern high speed pantographs reduce this mass even further by separating the horns from the head and placing them below the suspension. This is known as a *floating head* pantograph.

In many mainline and high speed pantographs the carbons are glued into an air channel, which is connected to a compressed air circuit. In the event of loss or excessive wear of a carbon strip, air pressure is lost and the pantograph *Auto-Drop Device*(ADD) lowers the pantograph, thus reducing the chances of damage to the OLE. Modern pans have a fast-drop capability to further reduce the risk of damage.

[113] Some low speed pantograph designs use a metallic strip instead.

[114] NR-L2-ELP-27715 "Overhead Contact System Design Specification Module 1: Fundamental Design Requirements"; Issue 1, March 2018; Network Rail; section 7.3.1.

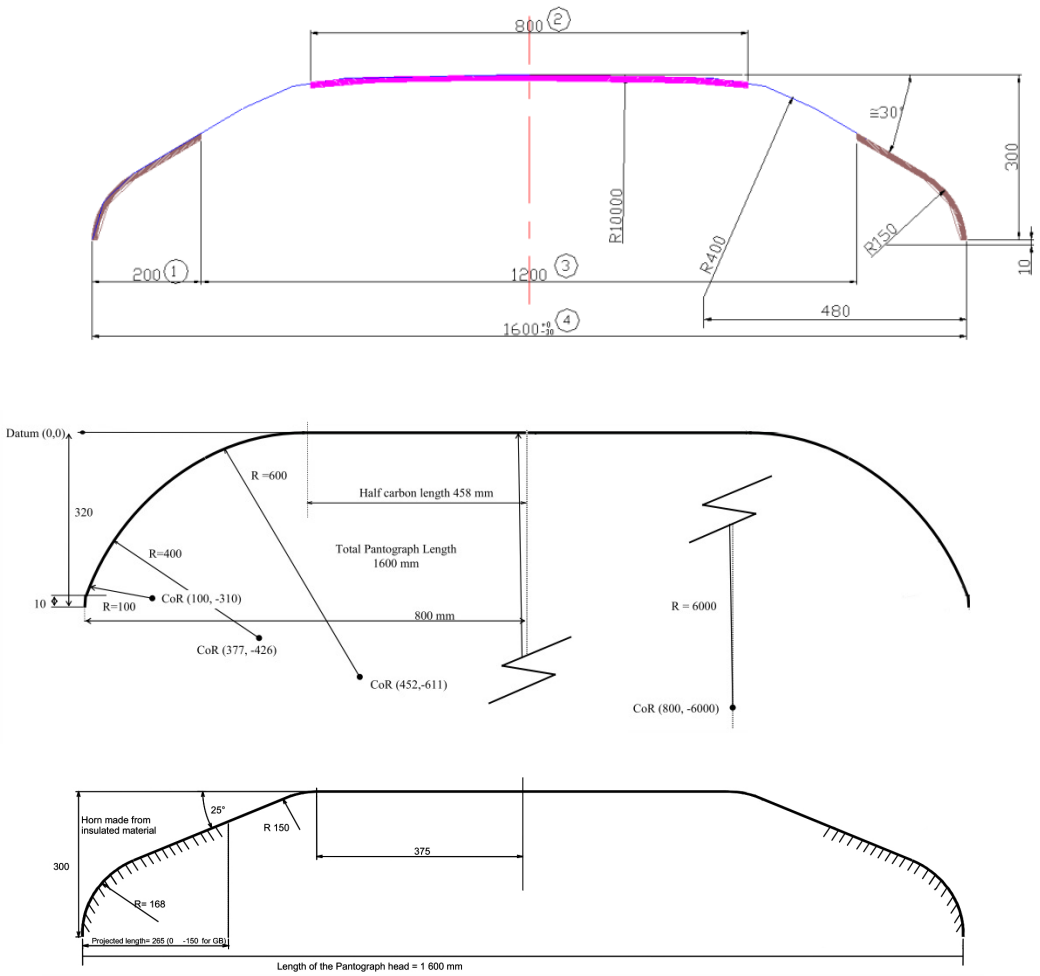


Figure 95: (top to bottom) Pantograph profiles: Europan, UK mainline, HS1[115]

All pantographs have a specified *operating range*; that is, the vertical distance over which they will safely operate, with a mechanical behaviour that is broadly the same. Pans with an auto-drop mechanism will generally also retract if the pantograph exceeds the upper operating limit.

The pantograph to contact wire interface is a complex one, comprising as it does three interacting dynamic systems (the pantograph, the OLE, and the train) each with various modes of movement.

The pantograph itself can be approximately modelled as a *spring-mass-damper* system. In simple terms, the pantograph is arranged to exert an upward force on the contact wire - the *contact force*. This is ideally a constant force, but several factors prevent this in practise. Aerodynamic effects on the pantograph are different depending on speed and whether the pantograph is *knuckle leading*

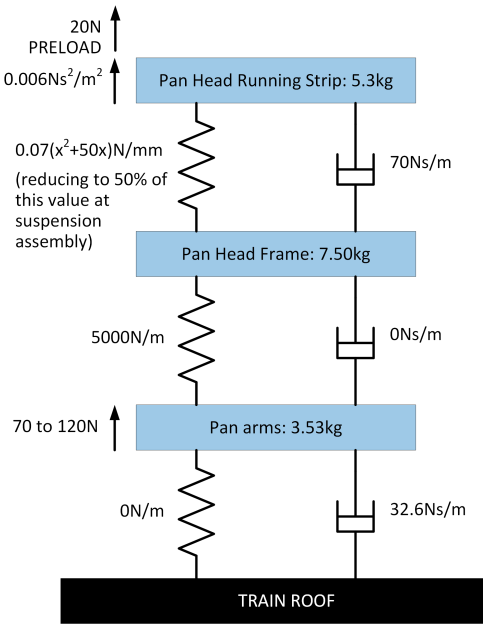


Figure 96: Brecknell Willis HS-X pantograph modelled as a spring-mass-damper system[116]

[115] BS EN50367:2020 "Railway Applications - Fixed Installations and Rolling Stock - Criteria to achieve Technical Compatibility between Pantographs and Overhead Contact Line"; August 2020; BSI; figures A.6, B.6, B.3.

[116] "Lump Mass Models for Legacy Pantographs on GB Mainline", S. Conway; November 2016; Current Collection Solutions/RSSB; p7.

or *trailing*. This can be partially overcome on modern pans by means of tuned aerofoils on the knuckle and/or head, and/or tabs on the horns to counteract the aerodynamic lever effect on the head.

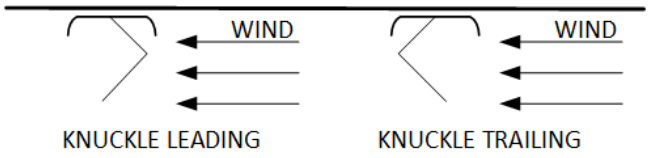


Figure 97: Different contact force depending on pantograph direction

The contact force also varies somewhat with wire height, due to the mechanical arrangement of the pantograph linkage and actuator[117]. Additionally, the friction of the knuckle itself can lead to varying force due to hysteresis, depending on whether the pantograph is rising or falling.

Figure 98: Brecknell Willis HS-P Mk1 pantograph with knuckle aerofoils and head tabs (arrowed). Kings Cross, UK

In Europe the design of pantograph-OLE interface is governed by the *Technical Specifications for Interoperability*[118] (TSIs), as transposed into European Standards, and these specify that a compliant AC OLE/pantograph system for up to 200km/h linespeed will have a contact force distribution such that the mean contact force $\pm 3\sigma$ (3 standard deviations) is always between 0 and 300N[119]. Static contact force is generally set at 70N or 90N at the pantograph. As dynamic contact force is added, higher forces will be seen at discrete features, and forces up to around 350N can be accommodated without risk of damage.

Pantographs at the front of a train experience higher levels of air turbulence, due to the nose of the train pushing

[117] On high speed systems, this problem is overcome by providing OLE at a constant contact wire height.

[118] The UK has now left the European Union and so the TSIs have ceased to apply. Their content has been transposed into the *National Technical Specification Notices* (NTSNs).

[119] BS EN 50119:2020 "Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines"; April 2020; BSI; section 5.2.5.2.

air around it. Airflow at the rear of the train tends to be smoother, so many administrations run their medium and high speed services using the pantograph at the rear of the train set, with the front one out of use in normal operation. This has the added advantage that in the event of a dewirement, the events will generally occur behind the front pantograph, leaving it undamaged and able to power the train after an incident.

11.1.1. Types of Pantograph

The UK currently has 11 different types of pantograph in active use; six on the mainline, 2 tram/metro types, and 3 which are confined to High Speed One (section 8.4). A full list can be found in Appendix C.

Early pantographs used a diamond linkage configuration (see figure 6 for an example), and later the cross-arm type was adopted; but a more sophisticated mechanical linkage design allowed parallelism to be maintained with a more responsive single arm[120]. In the UK this began to overtake the cross-arm design when the Stone-Faiveley AM/BR pantograph was introduced in 1959.

British Rail subsequently went into partnership with Brecknell Willis to develop a new single arm pantograph which would (after several iterations) be capable of reliable operation at speeds of 225km/h. The resulting *Brecknell Willis High Speed* pantograph became the template for most mainline railway pans in the UK[121], which all conform to the BR head profile shown in section 11.1.

The exception is on High Speed One, where a series of Faiveley high speed pans are used. These are matched to the French pattern OLE system on that route, having previously been used on TGV trains. HS1 pans use a different geometry with insulated horns, and have different dynamic characteristics. For this reason the HS1 pantographs are not permitted to run on UK conventional routes.

For the lower speeds of tram and metro systems it is not necessary to have the sophistication of secondary suspension or aerodynamic balancing, and so simpler pantograph designs are used.

Engineering development is now focused on active pantographs, where the contact force is measured many times a second and fed back to a controller which varies the actuator force. The Faiveley CX pantograph used in the 2007 speed record used this principle.

11.1.2. The Pantograph-OLE Interface

The contact force from the pantograph creates a vertical displacement on the contact wire – *uplift*. When the train is moving this uplift combined with the along track movement creates a mechanical wave in the contact wire. In simplified terms the pantograph can lose contact with the wire if the train catches up with the wave it creates. Since the speed of the wave is proportional to the square root of the wire tension, the OLE system designer will set the contact wire tension so that wave speed > 1.4 x maximum train speed. For higher speed systems this increased mechanical tension becomes a key constraint on the selection of conductors (section 11.16) and control of mechanical forces in line fittings (section 11.17.1) and OLE structures (section 11.10). Actual performance is however much more complex, due to higher order wave harmonics. These are affected by parameters such as presag (section 11.2), dropper spacing and discrete features in the wire.

A key factor in the system performance is the *elasticity* (measured as uplift per unit of contact force) of the OLE. Ideally this would be uniform throughout the system – however in reality the elasticity is less at the OLE

[120] Invented by Louis Faiveley in 1955.

[121] For more information on the development of the BWHS pantograph visit Dave Coxon's train testing site at www.old-dalby.com/HSCCP.htm.

structure, due to the support arrangement on the catenary restraining the system, than at the midspan between structures.

Therefore the OLE system designer will match the *elasticity differential* in the system to the performance requirements. The higher the linespeed, the lower the required elasticity differentials (section 11.2). For high speed systems, the absolute elasticity must also be controlled, to counteract the increased dynamic contact force and keep uplifts within the available movement of the OLE.

All mainline and high speed systems have a maximum *free uplift* capability - that is, the degree of uplift that registration arms (section 11.13.2) and other components must cater for. This is usually set to twice the value of the maximum *design uplift* derived from measurement or modelling, to provide a factor of safety[122]. Free uplift values for UK mainline systems vary from 160mm to 300mm.

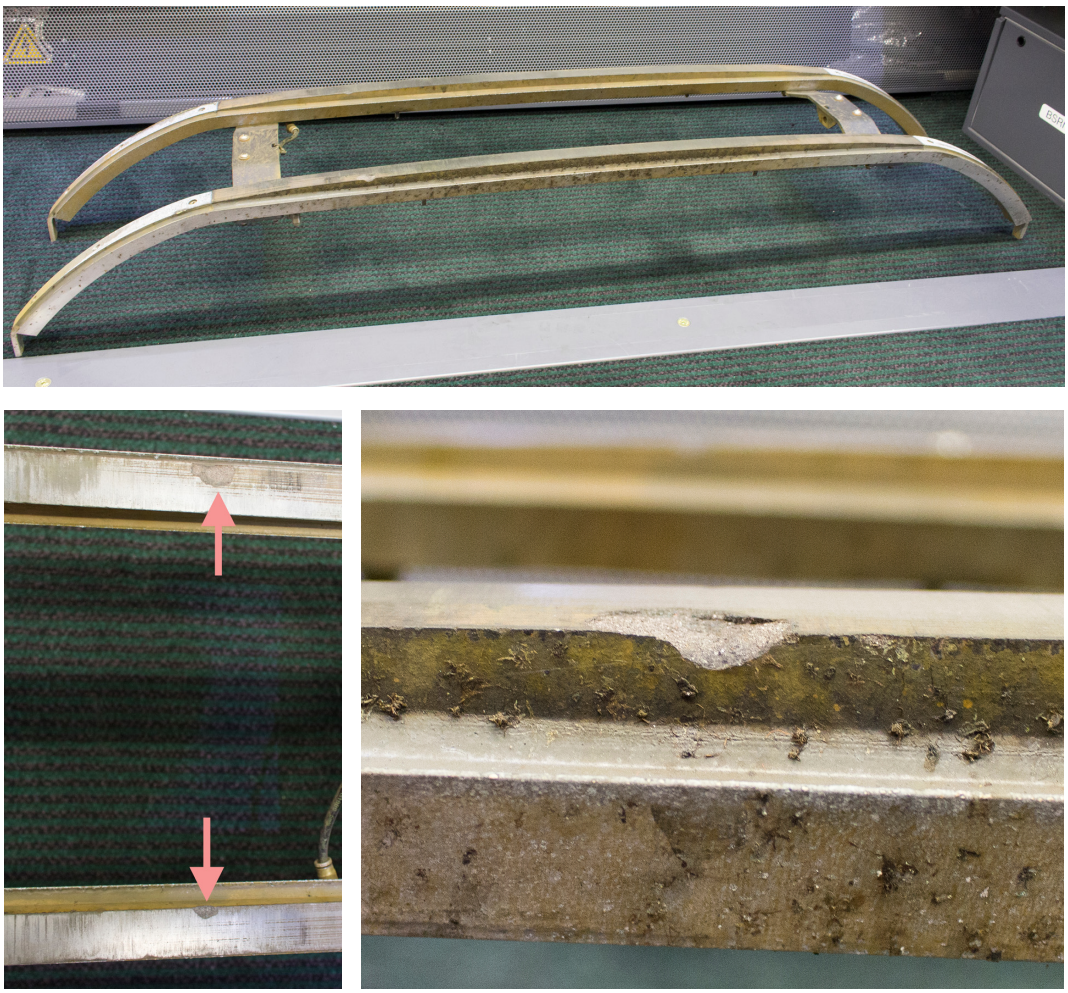


Figure 99: (clockwise from top) Pantograph head damaged by OLE defect, close-up of chipping, top view of chipping (arrowed)

Trains with multiple pantographs pose a further problem; the wave travelling backwards from the front pantograph can interfere with current collection at the rear pantograph. OLE systems designed to run with multiple pantographs at high speed therefore require particular care in the selection of tension and droppering.

A further problem is that of *hard spots*; any component attached to the contact wire - such as a dropper clip (section 11.16.4) or registration arm (section 11.13.2) – reduces the elasticity locally, and each hard spot will

[122] BS EN 50119:2020 "Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines"; April 2020; BSI; section 5.10.2.

reflect a portion of the wave back towards the train. Excessive hard spots will lead to loss of contact at the pantograph, and can cause damage to the carbons which then create a vicious circle of OLE/pantograph damage.

Conversely, an over-tensioned z-dropper (section 11.10.11) can lead to hogging which will also affect dynamic performance.

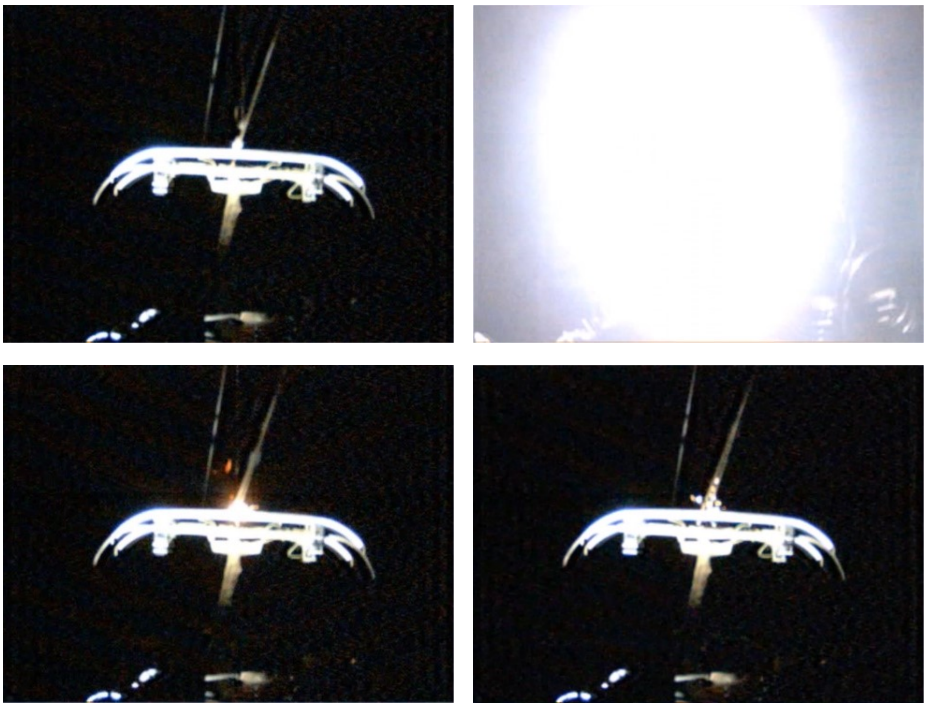


Figure 100: Loss of contact and arcing caused by poorly adjusted dropper

Heating effects can be significant at the pantograph/contact wire interface – a particular issue when the train is stationary and aerodynamic cooling is not available. For this reason trains may have limitations on their power consumption when at rest. The contact area must be set according to current requirements, and DC pantographs (needing higher currents) have either a larger contact area with multiple carbon strips, or use multiple pans.

Figure 101: Brecknell Willis DC pantograph with four carbon strips

11.2. Suspension Arrangements

Various suspension systems have been developed for the different performance requirements of OLE.

At its simplest, OLE can consist of a contact wire suspended directly from support structures. This is known as *tramway* or *trolley* OLE.

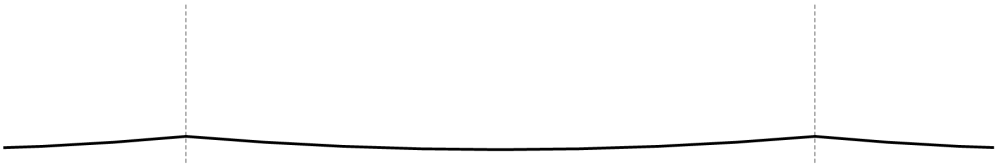


Figure 102: Tramway OLE

Although simplest in terms of engineering, the elasticity is zero at the support point and very high at the midspan; and since there is no support to the contact wire between structures, spans are typically limited to 40m. For these reasons, it is suited only to very low speed ($\leq$30km/h) lines for tram networks and heavy rail sidings.

The tram system can be improved by the addition of a *stitch* (also known as a *bridle*). Here the support is transferred to the stitch wire, which in turn suspends the contact wire. The length of stitch may be varied for the particular system.

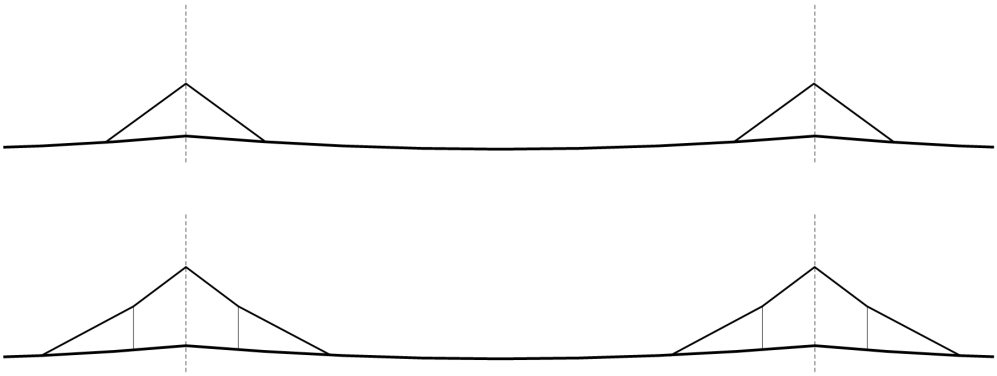


Figure 103: Stitched tramway OLE

The stitch creates some elasticity at the support, and this type of suspension is often used on tram systems, giving good current collection up to 80km/h.

The next step is to create a suspension wire running the whole length of the system. This is the *simple catenary* system – so called because a wire suspended in space describes a catenary curve[123] under gravity. The contact wire is suspended from the catenary by vertical droppers.

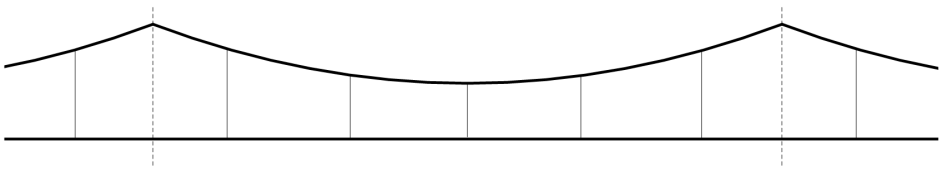


Figure 104: Simple catenary OLE

[123] Technically a suspended wire describes a *cosh curve* rather than a true catenary, but the differences are very small.

This system gives better elasticity at the support and is the simplest system adequate for mainline railways. For this reason it is widely used around the world, and gives good current collection up to 120km/h. It also provides the additional cross section necessary for delivering increased traction current.

Above this speed there are three options available. The first option modifies simple equipment to use a *presagged* contact wire. Rather than keeping the contact wire flat across the span, a deliberate amount of *sag* is introduced between the first and last droppers – typically of 1/1000 or 1/2000 of the *span length* (the distance between structures).

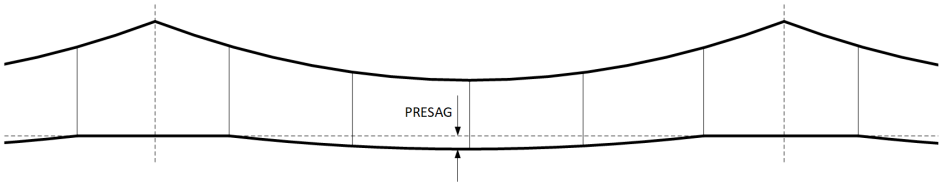


Figure 105: Presagged simple catenary OLE

The purpose of the presag is to compensate for the greater elasticity at the midspan, since the uplifted contact wire position at midspan is closer to the uplifted position at the support. This system has found favour in the UK and France, and works at all speeds – this system powered the current rail world speed record holder (section 7.3).

It is also possible to introduce a stitch wire into simple catenary. The tension in the stitch can be set so as to increase the elasticity at the support and so reduce elasticity differential even further.

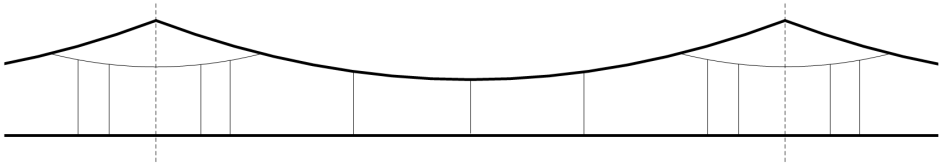


Figure 106: Stitched simple catenary OLE

This system is favoured on high speed lines in Germany, where it is used for speeds up to 300km/h. Some German stitched systems also have presag[124]. The UK trialled stitched equipment in the late 1950s, but it was subsequently removed on all but the Brown Boveri system (section 13.2.5).

A further development is the introduction of a third wire – the *auxiliary catenary*. This gives us the *compound catenary* system.

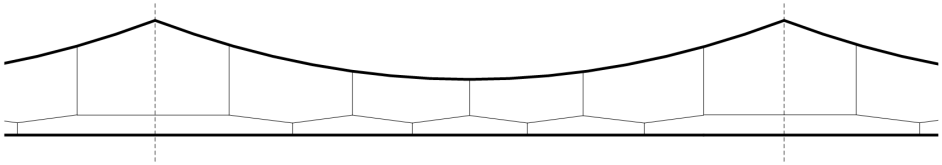


Figure 107: Compound catenary OLE

This also gives very low elasticity variation, and many of the first mainline systems in the UK were compound.

[124] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p160.

It has since fallen out of favour in the UK due to the complexity and maintenance requirements. Elsewhere in the world it is still widely used, notably in Japan, where the Shinkansen lines (section 8.4) make extensive use of compound equipment at speeds up to 300km/h.

11.3. Tensioning Arrangements

OLE must be tensioned to maintain the contact wire height under gravity. Contact wire tensions run from 8kN for slow speed systems, right up to 40kN (used for the world speed record attempt). Typically, mainline systems run between 10 and 20kN.

The tensioning arrangements must take account of the expansion and contraction of the wires with varying temperature. Each system has a defined *temperature operating range*, and a complete length of OLE (or *wire run*) will expand and contract as much as 1.5 metres over a typical range[125]. This has a major effect on tensioning arrangements.

The simplest system is known as *Fixed Termination* (FT). Here the catenary is fixed and tensioned at every structure. The contact wire is tensioned at each end, and allowed to expand and contract in between, but is restrained by the droppers attached to the catenary.

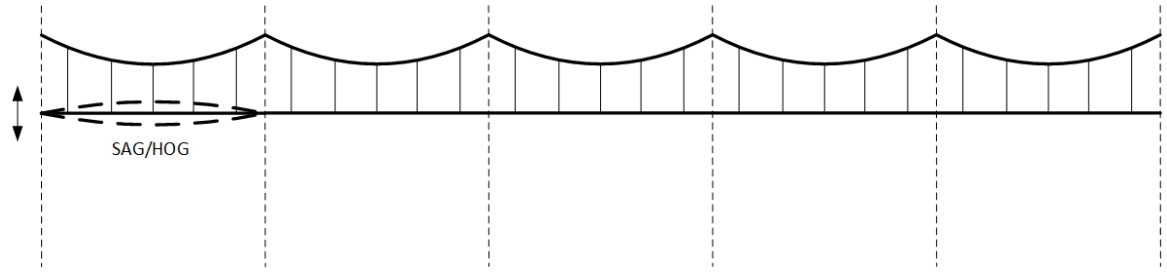


Figure 108: Fixed termination OLE

As temperature increases, the contact wire will sag between structures. As it decreases, the contact wire will *hog*. This change in profile will affect the system dynamics; for this reason, FT systems are not suited for higher speeds, and are generally only used on tram and sidings systems.

Care must be taken when designing FT systems to ensure that all fittings can withstand the maximum tension in the system. FT cantilevers are configured to pivot in the vertical plane, so that tension changes do not stress the cantilever frame, while using the frame weight to prevent large tension differences between spans.

Figure 109: Fixed termination portal cantilevers. Euston, UK

The standard system for medium and high speeds is the *Auto Tensioned* (AT) system. Here the catenary is fixed only in the centre of the wire run at the *midpoint anchor*; the whole system is free to move around this fixed point. Constant tension is provided by a tensioning device – traditionally by a set of balance weights attached to the catenary and contact wire.

[125] For example, modern UK mainline systems are designed to operate in an ambient air temperature of -18°C to +40°C.

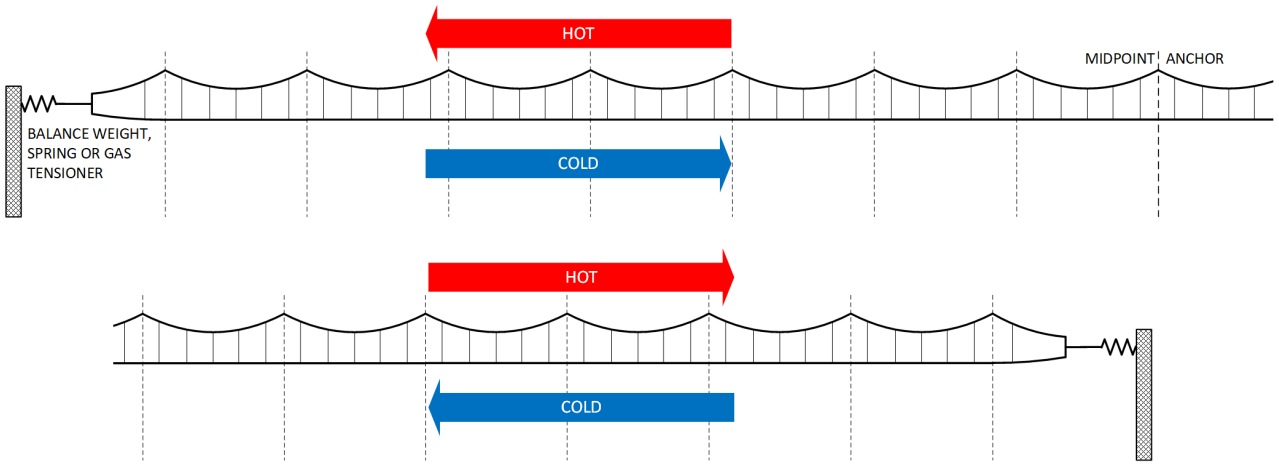


Figure 110: Auto tensioned OLE

Figure 111: Siemens drum type anti-fall balance weight assembly; point of engagement of anti-fall wheel with stop arrowed. Rugby, UK

Mechanical advantage of 3:1 – or for higher tensions, 5:1 – reduces the size of the weight stack required, and is provided via *pulleys* or *drumwheels*. The weights travel up and down the mast as the system expands and contracts. A single set of weights can tension both contact wire and catenary, but modern mainline and high speed systems typically have independent tensioning of the two wires.

Balance weights are a significant hazard in the event of a dewirement – without a means of stopping the fall of the weights, they can be a hazard to staff and to passing trains, and (for independently tensioned systems) cause further OLE damage via dropper breakage.

Figure 112: Pfisterer helical spring tensioners (cams arrowed). Forest Gate, UK

For this reason modern balance weight assemblies use a drumwheel which includes an *anti-fall* mechanism; usually a simple toothed wheel which engages with a ratchet stop in the event that tension is lost. This prevents further fall of the weight stack. Balance weights on tram systems are usually configured to travel inside the support mast to avoid these issues and prevent vandalism.

Balance weights are simple and robust, but for mainline railways where reliability is critical and maintenance access limited, they suffer from a number of disadvantages. The need for vertical travel means they must be placed on a mast, and for multi-track railways this means the OLE on inner tracks must be routed out to the mast; either using a set of right angle pulleys at a portal, or by threading the wire run directly through the outer track OLE to the mast. The former system introduces complexity and failure modes, and the latter means that wire runs are interconnected and no longer have mechanical independence. Weight theft can also be an issue when metals prices are high.

Figure 113: 3:1 ratio pulley type balance weight anchors. Winson Green, UK

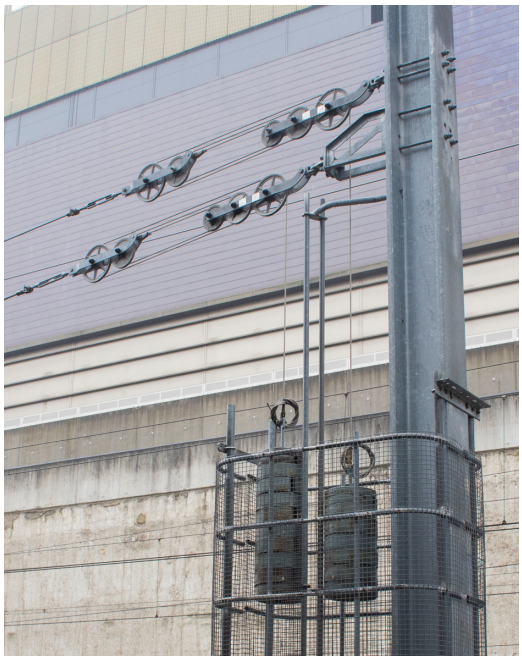


Figure 114: 5:1 ratio pulley type balance weight anchor for high speed equipment. Stratford, UK

A recent development is the use of spring tensioners instead of balance weights. These maintain a constant tension by using a mechanical spring. Since a spring applies a force in accordance with the equation $F = kx$, the tension would ordinarily vary with the spring extension. To eliminate this, a shaped cam is used to provide a constant force. The tensioners are often placed over the track for ease of maintenance access using rail-mounted plant. Spring tensioners come in varieties which use a helical spring, and a more compact arrangement using a spiral torsion spring.

All tensioners have an efficiency of less than 100%, caused by the friction within the tensioner mechanism. Tensioner efficiency should be at least 97% for good performance.

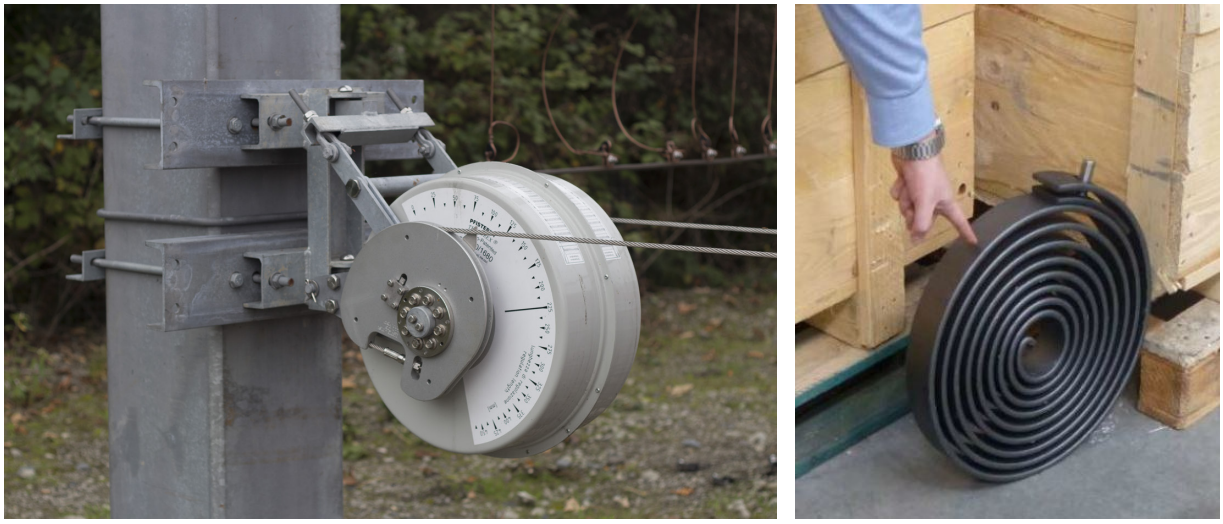


Figure 115: (l-r) Pfisterer Tensorex C+ spiral torsion spring tensioner, and Tensorex spring

Whatever tensioning device is used, along track movement is provided for at intermediate structures by pulleys, flexible *links* or pivoted *cantilevers*. Only the catenary supports closest to the midpoint anchor can be directly clamped. The tension is not entirely constant, varying slightly due to the *drag* caused by cantilevers pivoting the wire away from the neutral temperature position. However with good design, the tension variation can be kept below 3%. Cantilevers in AT systems pivot in the horizontal plane so as not to unduly influence the contact wire profile, and so it is important to limit *stagger change* as the rotation of the cantilever moves the wire away from its design position.

Figure 116: (l-r) Clamp, link and pulley catenary supports. Ealing, UK

Other tensioning devices are sometimes substituted, such as gas systems where space is restricted. These have the disadvantage that their travel is proportional to the change in gas pressure, and therefore ambient temperature rather than wire temperature (which can be significantly higher or lower). They cannot therefore provide a constant wire tension.

Some administrations, including the UK, have experimented with hybrid systems, with auto-tensioned catenary and fixed termination contact wire, or vice versa. These arrangements were shown not to provide good performance and are not used in modern systems.

11.4. Tension Lengths and Overlaps

The length of a wire run is limited[126] due to the maximum drag and stagger change requirements detailed above – as well as practical considerations such as maximum wire length on the wire drum (section 19.12). OLE is therefore split into *tension lengths* (also known as wire runs). Turnouts and crossovers are provided with their own wiring (section 11.5), and due to the shorter length of OLE needed are often provided with a *half tension length* comprising a tensioner (section 11.10.10) at one end, a fixed anchor at the other, and no midpoint anchor (section 11.10.11).

At the end of each tension length (or half tension length) arrangements must be made to transfer the pantograph from one tension length to the next. This transfer arrangement is known as an *overlap*. At its simplest, an overlap is a purely mechanical arrangement. However, it is also a convenient place to create an electrical break in the OLE for sectioning purposes.

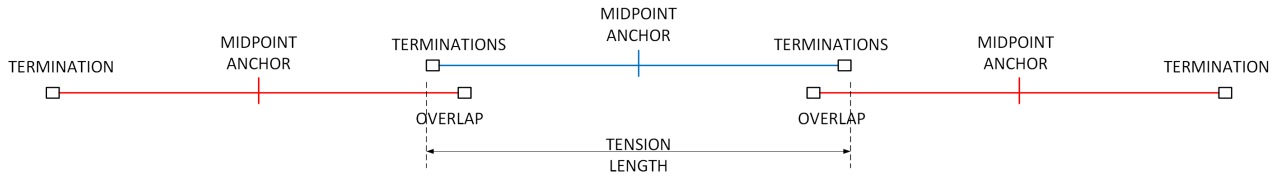


Figure 117: Tension Lengths, Overlaps and Midpoint Anchors

The overlap type is defined by two parameters; the number of spans of *parallel running*; and whether it is *uninsulated* (also known as a *construction overlap*) or *insulated*.

An insulated overlap takes advantage of the fact that each wire run has a zone where it is *out of running* (not in contact with the pantograph). At this point insulation can be inserted in each wire without the complication of an *in running* type insulator. An isolator (section 11.7) or booster transformer (section 10.4.2) may then be connected around the electrical break.

It is important when configuring overlaps to ensure that electrical continuity is provided (through uninsulated overlaps) and that all wire run sections are at the same *electrical potential* (for insulated overlaps). This is achieved by applying flexible *jumpers* between wire runs. For electrical continuity *current carrying jumpers* are used, and these are generally duplicated to provide redundancy. For voltage equalisation *equipotential jumpers* are used.

Figure 118: (l-r) Jumper types; current carrying, equipotential, C-jumper

A third type of jumper, the *C-jumper*, is used to provide current sharing between contact wire and catenary in systems which do not have current carrying droppers (section 11.16.4).

[126] For example, UK mainline systems have length limits varying from 1500m to 1970m.

It should be noted that, when used as an electrical break for a booster transformer, a train brought to a stand in the overlap will short out the booster transformer. This can lead to arcing and contact wire burnout, and for this reason overlaps are placed carefully relative to signals.

11.4.1. Single Point Overlap

The simplest form of overlap is the *single point*; this has a single point of transfer, with no spans of parallel running.

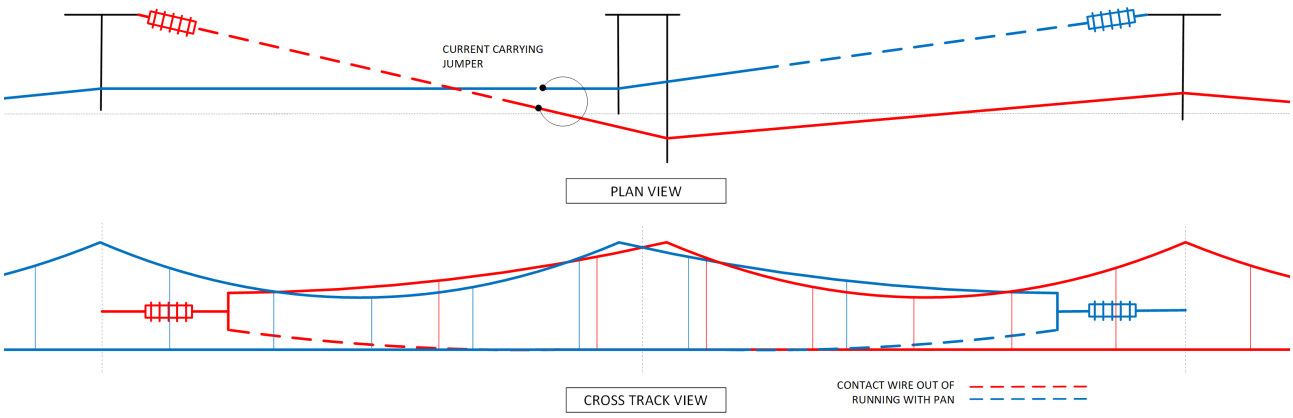


Figure 119: Uninsulated single point overlap

This arrangement is only suitable for low speeds on tram and siding systems, due to the relatively hard spot and short length of the transfer zone.

11.4.2. Single Span Overlap - Conventional

Higher speeds are achievable using a *single span* overlap. This has a single span of parallel running. The pantograph is transferred gradually from one wire run to the other; within the parallel running section, it is in contact with both. The out of running contact wire is set 300-500mm above the in-running wire at the structures depending on the system parameters.

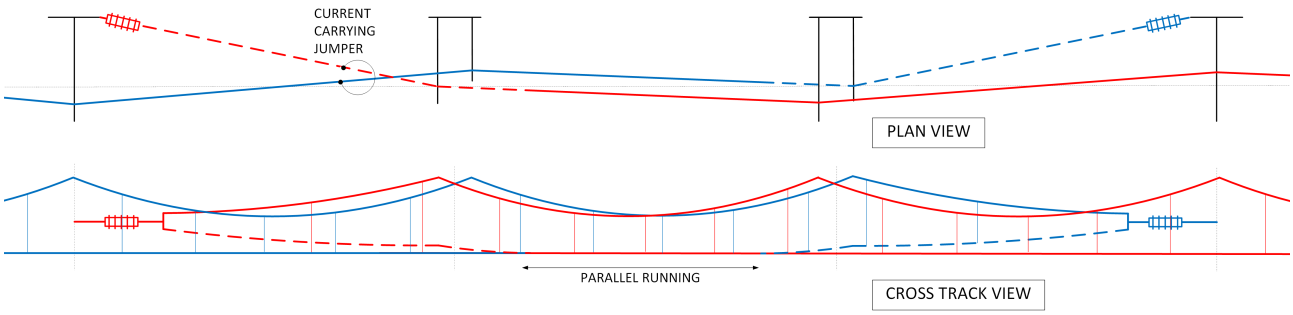


Figure 120: Uninsulated single span overlap

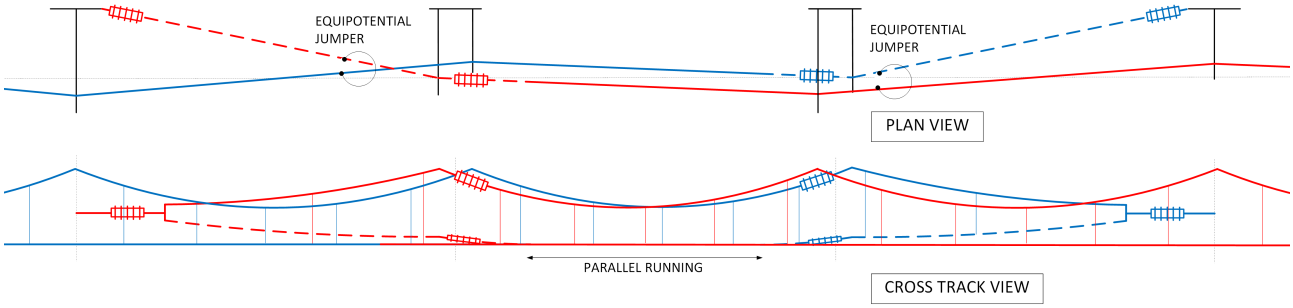


Figure 121: Insulated single span overlap

The single span overlap is used worldwide, and is the standard for UK heavy rail up to 200km/h. To confuse matters, many reference sources refer to this arrangement as a three span overlap.

11.4.3. Single Span Overlap – Without Anchor Spans

A recent development in the UK is to remove the anchor spans from the single span overlap and terminate each wire run at the end of the overlap span. Without careful design this would result in poor pantograph dynamics, but it is possible to adopt a very specific vertical profile, using the *natural rise* or *circumflex* of the contact wire to ensure good parallel running. A pulley is mounted below the spring tensioner (section 11.3) to ensure that the height of the terminating contact wire remains constant. This arrangement has been proven for speeds up to 200km/h but requires careful setup and maintenance.

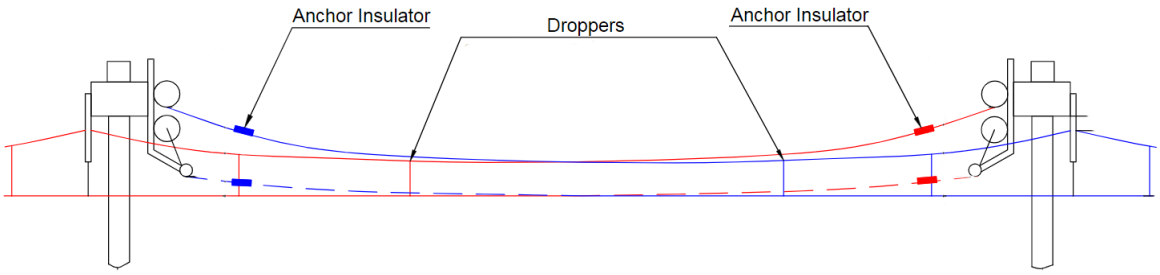


Figure 122: Series 1 single span overlap configuration

Figure 123: Series 1 single span overlap anchor with underslung pulley. Swindon, UK

11.4.4. Multiple Span Overlaps

For higher speeds, the increased elasticity variation created by the wire being lifted out of running, and waves being reflected back from the anchor (section 11.10.10), become barriers to good current collection. Therefore the number of spans of parallel running is increased. High speed OLE typically uses two span overlaps.

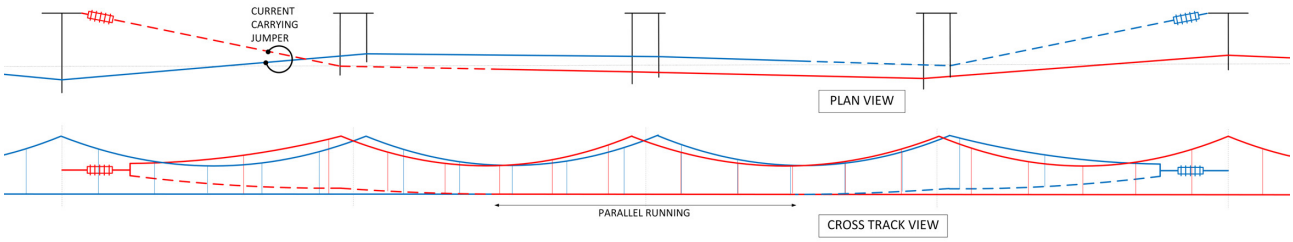


Figure 124: Uninsulated two span overlap

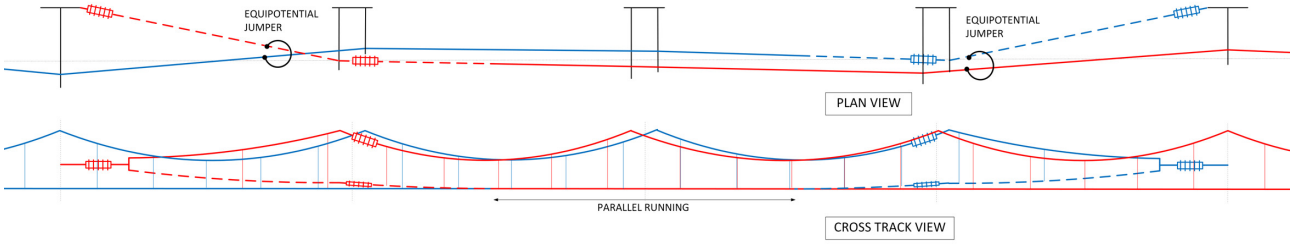


Figure 125: Insulated two span overlap

This system is used on European high speed lines at up to 300km/h. Some high speed lines use three, four or even five span overlaps.

11.4.5. Overlaps in Multi-track Areas

Wiring of overlaps and crossovers becomes more complex in multi-track areas, particularly on systems which exclusively use tensioners on masts; it becomes necessary to extend the conductors on inner tracks through those on the outer tracks to reach a mast. This is most easily done by merging the wire run conductors into a single wire, known as a *tail wire*. This is done using an equalising plate (section 11.17.1) and allows the wire run to pass between the catenary and contact wire of the outer track(s).

Figure 126: Tail wire (shaded red) splitting into full equipment. Peterborough, UK

11.5. Turnout and Crossover Wiring

Special arrangements are required where tracks diverge, converge or cross, to ensure continuity of current collection and minimise dewirement risk. A second wire run is required to service the crossover, and introducing this additional contact wire brings with it the risk of *hookover*, where the contact wire enters the space at the end of the pantograph (section 11.1), and then gets underneath the pantograph head with catastrophic results. This risk rises with speed, and is exacerbated when the pantograph raises the in-running contact wire, since the second wire does not rise at the same time.

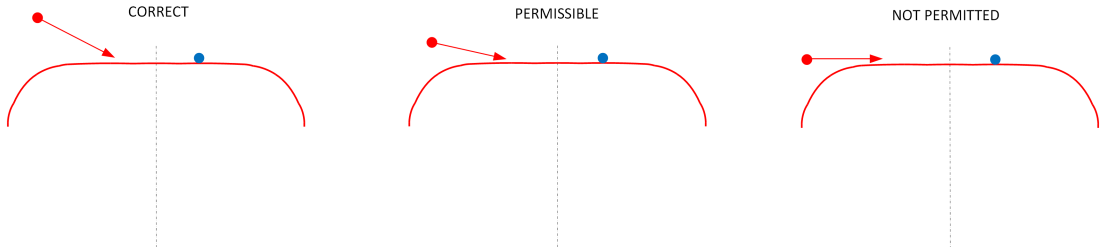


Figure 127: Hookover risk for different wire/pantograph interactions

Even if hookover is avoided, incorrect turnout wiring geometry can lead to contact wire *side wear*, caused by the wire repeatedly running up the pantograph from the end of the horn and wear strip. Side wear often leads to early failure of the wire or dewirement when a pantograph strikes a fitting.

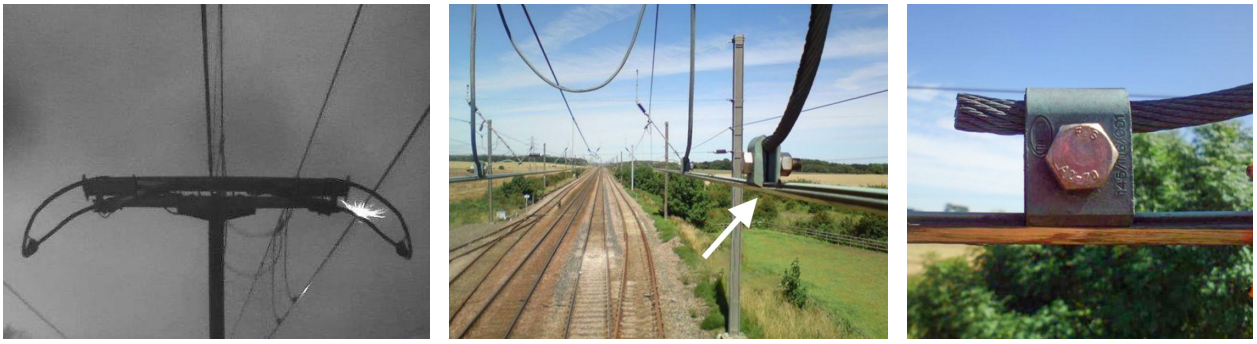


Figure 128: (l-r) Contact wire side wear in progress, side wear at a turnout (arrowed), close up of side wear threatening jumper clamp

11.5.1. Fitting Free Zone

To minimise this risk, European systems adopt the concept of the *Fitting Free Zone* (FFZ). This zone encompasses the space around the end of the pantograph, including the horns. The goal is to ensure that no contact wire clips or clamps (other than dropper clips, which are unavoidable) enter the space at the end of the pantograph. This minimises the risk of damage from a fitting bolt if a contact wire is not completely vertical, during the period when it runs up from the horn area onto the contact strip.

Fittings which are excluded from the FFZ include:

- Registration arms (section 11.13.2) - it is permissible for the arm to cross the FFZ, but the contact wire clip should be outside the zone;
- Section insulators (section 11.6.1);
- Jumper connections (section 11.4);
- Tensioned connectors (section 11.4);
- Out of running contact wires (permitted but not preferred).

The FFZ begins horizontally at the point where the pantograph head begins to curve downwards, and ends a short distance beyond the end of the horn to allow for sway (section 11.13.2). Vertically, it typically extends

from a distance above the pantograph plane equal to the free uplift (section 11.13.1) to the same distance below it. Once defined, the FFZ is applied to standard turnout geometries[127] and used to develop the permissible wiring geometry to be used.

Fitting free zones are defined for OLE systems in most countries in Europe[128], but are not defined or used in the UK, with the exception of the recently-introduced GEFF (section 13.4.2) and Series 1 (section 13.4.4) systems.

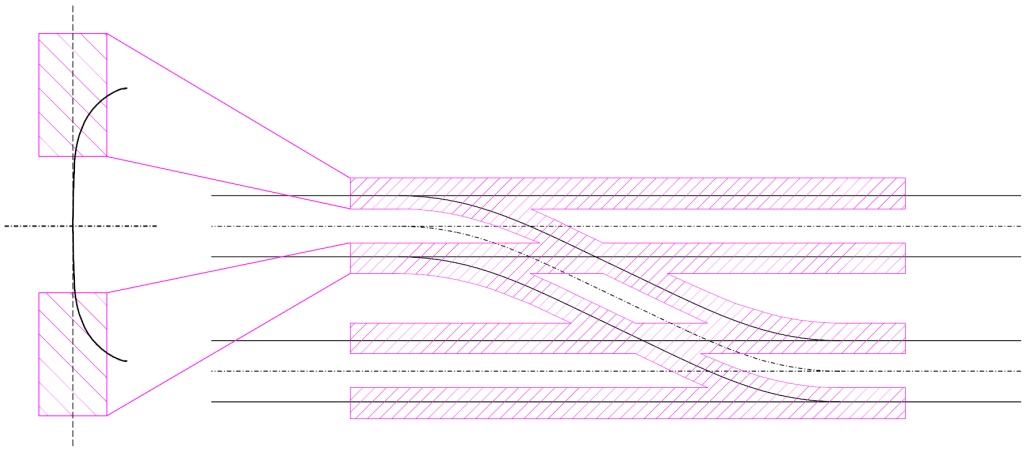


Figure 129: (l-r) Series 1 Fitting Free Zone[129] around GB profile pantograph, and zone applied to a UK 40mph Ev geometry crossover

11.5.2. Turnout Control Structure

At the core of the turnout arrangement is the *control structure*; an OLE structure placed at a specific point in relation to the *turnout*. In Europe the position of the control structure is determined using the fitting free zones as the starting point; but in UK systems it is predefined for specific OLE systems based on the distance between the stock rail and switch rail of the turnout - the *toe opening*.

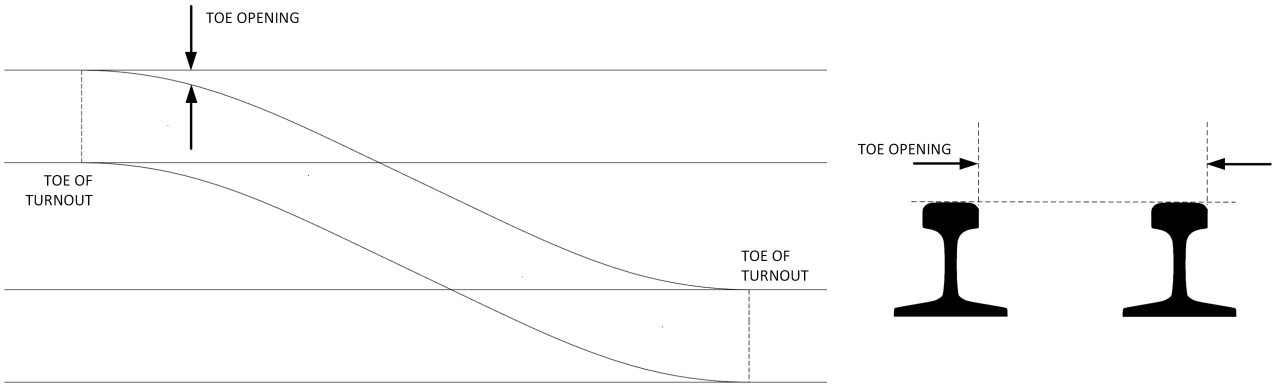


Figure 130: Toe opening for a turnout

Some systems place the control structure at a toe opening of between 180mm and 330mm (with a nominal

[127] All turnout diagrams in this section are stretched 10x in the cross-track direction for clarity.

[128] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p360.

[129] M.01.340 "Fitting Free Zone"; Rev C, 2012; Network Rail/Furrer+Frey.

value of 200mm)[130], and others 200mm to 350mm (nominal value 300mm)[131].

The following sections set out the various ways that turnout wiring and control structures can be arranged, and are illustrated using typical UK turnout geometry and fitting free zones.

11.5.3. Low Speed Tangential Method

The simplest way to wire a turnout is to use an additional wire run for the turnout, with no connection between the two wire runs and pantograph transfer at the control structure.

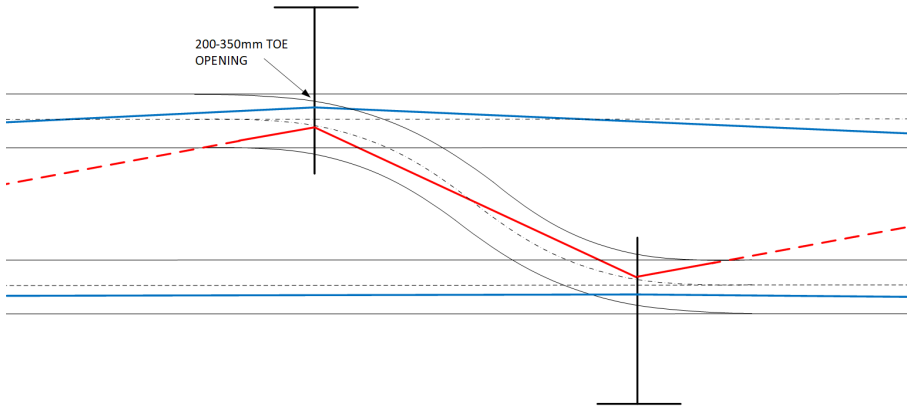


Figure 131: Low speed tangential crossover wiring

This is satisfactory for low speeds, and is used extensively on trams systems and in heavy rail sidings. Fitting free zones are not required for low speed situations as the uplift (and therefore hookover risk) is negligible.

11.5.4. Cross Contact Method

One method used to minimise the hookover risk at higher speeds is to use a *cross contact* arrangement. In this case the two wire runs cross, and a *cross contact bar* is provided at the contact wire crossing point, which is set inboard of the control structure - but outside of the fitting free zone - by careful staggering. The cross contact bar ties the two wires together while allowing for along-track movement. The most frequently used wire (usually the mainline) is placed below the second (usually crossover) wire; this ensures that the wire run which is not in contact with the pantograph follows the lifted wire, so that hookover risk is minimised.

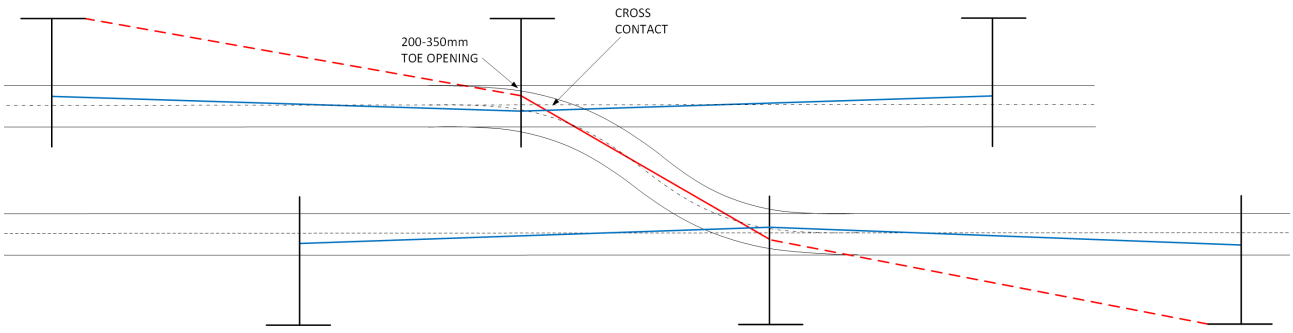


Figure 132: Traditional cross contact crossover wiring with mast anchors

[130] 141667-FAF-MAN-EOH-000002 "UK Master Series - Allocation Design Manual"; Issue 1.8, 2017; Network Rail; section 13.11.

[131] 118049-FAF-MAN-EOH-000001 "Series 1 OLE System - Allocation Design Rules Manual"; Issue 6.2, 2016; Network Rail/Furrer+Frey; section 13.5.1.

This configuration (and all the subsequent ones in this section) creates a mechanical connection between the two wire runs, so it is important to consider relative along-track movement (section 11.3) of the two conductors and ensure that it remains within the limits imposed by those connections. For this reason, the fixed anchor end of the crossover wire run location should be located close to the midpoint anchor (section 11.10.11) or fixed anchor of the mainline wire run.

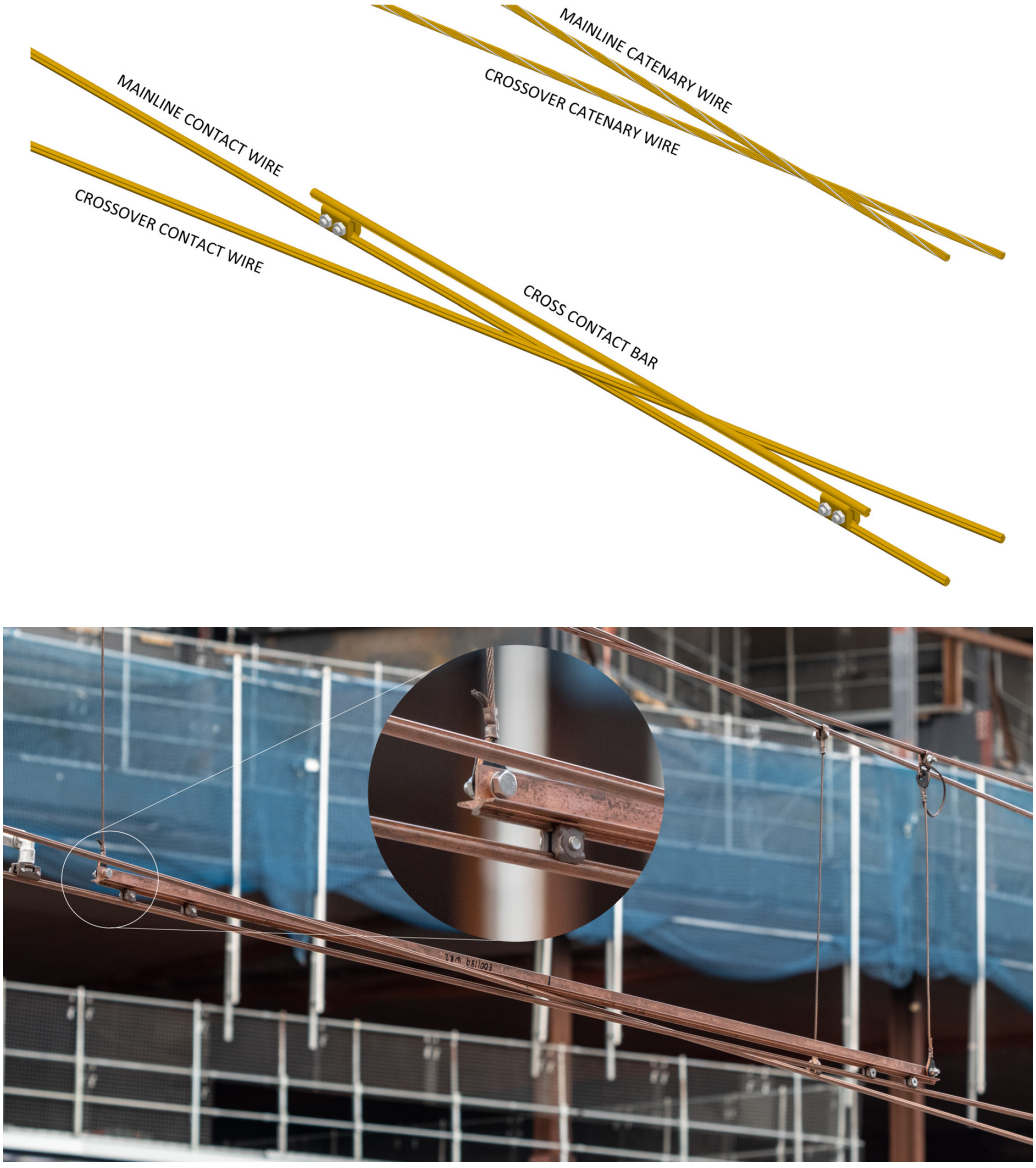


Figure 133: (top to bottom) Traditional cross contact bar general arrangement, Siemens cross contact assembly with T-bar detail

The cross contact arrangement was the UK standard from the introduction of OLEMI equipment (section 13.3) in the 1970s onwards. At this time the fitting free zone concept was not used in the UK, and so turnouts which use OLEMI geometry often place fittings close to, or even within, the fitting free zone.

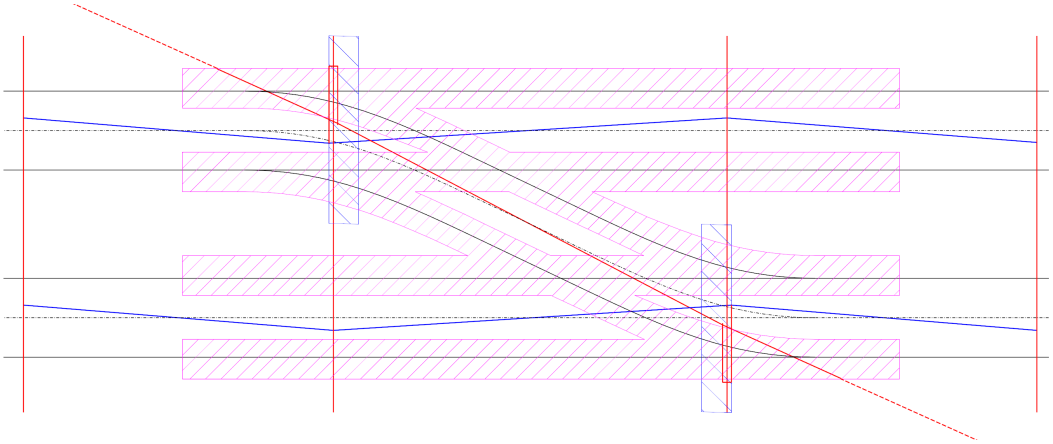


Figure 134: OLEMI standard cross contact geometry (with mast anchors) relative to fitting free zone for a 40mph Ev crossover[132]

More recent systems such as Series 1 (section 13.4.4) and UKMS (section 13.4.5) adopt different toe openings and staggers, and keep fittings outside of the zone.

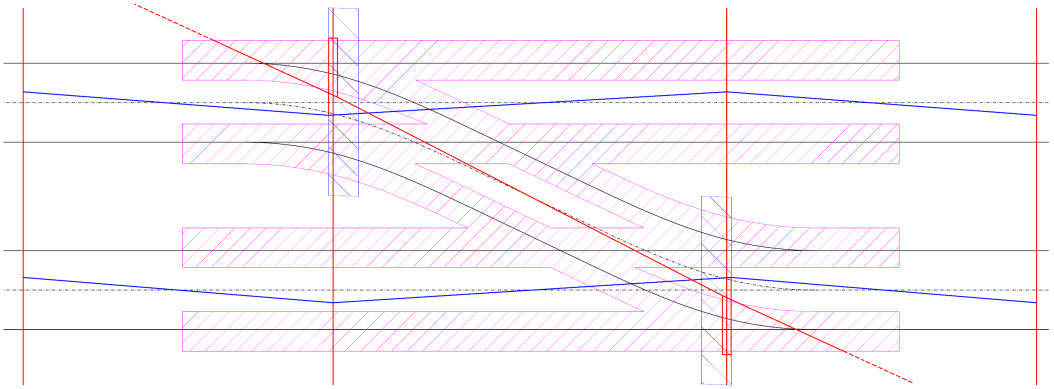


Figure 135: UKMS standard cross contact geometry (with mast anchors) relative to fitting free zone for a 40mph Ev crossover[133]

The cross contact system has been used extensively in UK heavy rail - although the cross contact bar can cause a hard spot if poorly designed, leading to fatigue of the bar, and the bolts for the bar have a tendency to loosen and fail. For this reason use in the UK is now limited to speeds below 160km/h or where there is no practical alternative. Cross contact has however been successfully used in Europe with a specially-designed T-shaped cross contact bar and appropriate droppering.

[132] Toe opening zone shown in this and subsequent drawings in blue hatching. Turnout staggers are +350/-230mm relative to relevant track, structure placed at 200mm toe opening. UK1/006/202 "Crossover Arrangement for Cantilevers (Mk1)"; Rev 05, 2003; Network Rail. Note that the cross contact bar is clear of the FFZ, but the crossover wire run registration point is close to the FFZ.

[133] Geometry is as previous diagram, except that crossover staggers are +320. MS/B06/B02/A3 "Crossed Contacts Crossover General Arrangements"; Rev 01, 2017; Network Rail. Note that the registration point is now clear of the fitting free zone.

11.5.5. High Speed Tangential Methods - UK1

Modern UK systems have moved away from the cross contact arrangement for the reasons given above, and instead adopted a more sophisticated form of tangential arrangement.

The first system to do so was UK1 (section 13.3.7), used for the West Coast Route Modernisation. This used a specific droppering arrangement and a span where the two wire runs are in parallel on the lead up to the control structure, to ensure that the pantograph picks up the crossover wire run without hookover risk.

Figure 136: UK1 tangential wiring (diverging route behind photographer). Ledburn Junction, UK

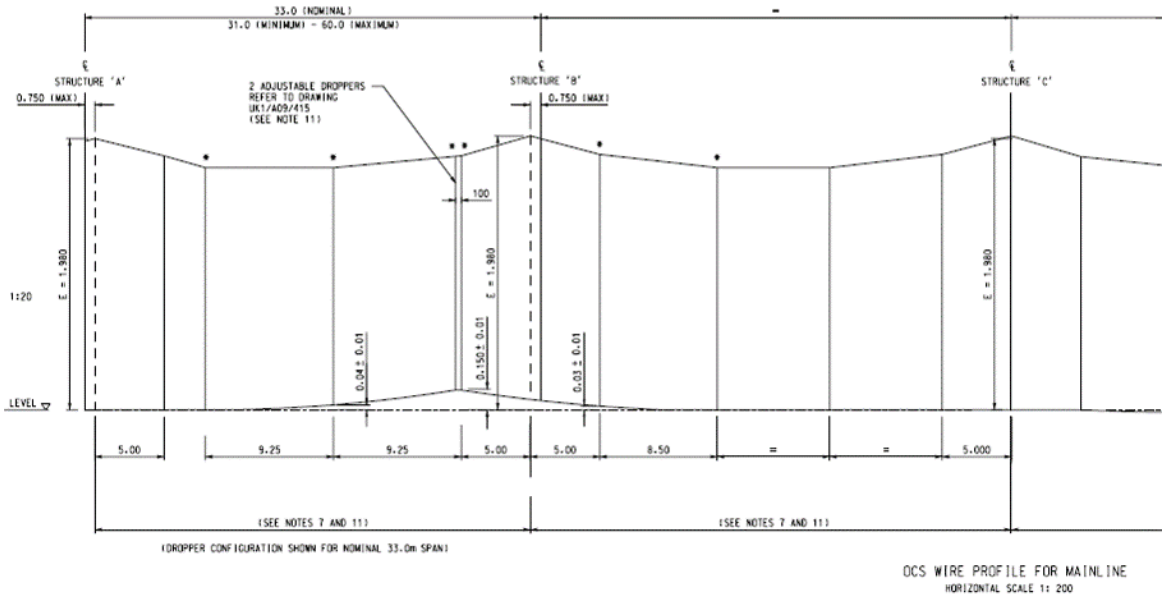


Figure 137: UK1 tangential wiring - profile view showing double dropper

11.5.6. High Speed Tangential Methods - Modern Approach

The UK1 tangential system, though effective, was felt to be overly-complex and hard to set up and maintain. For this reason, the latest Series 1 (section 13.4.4), Series 2 (section 13.4.3) and UKMS (section 13.4.5) designs instead use a simple tangential arrangement with one, or preferably two, spans of parallel OLE before the control structure, and cross-droppering (section 11.5.7) at the turnout. Anchoring is usually provided on a portal boom (section 11.10.10) thus keeping the crossover wire run over the pantograph and further minimising hookover risk.

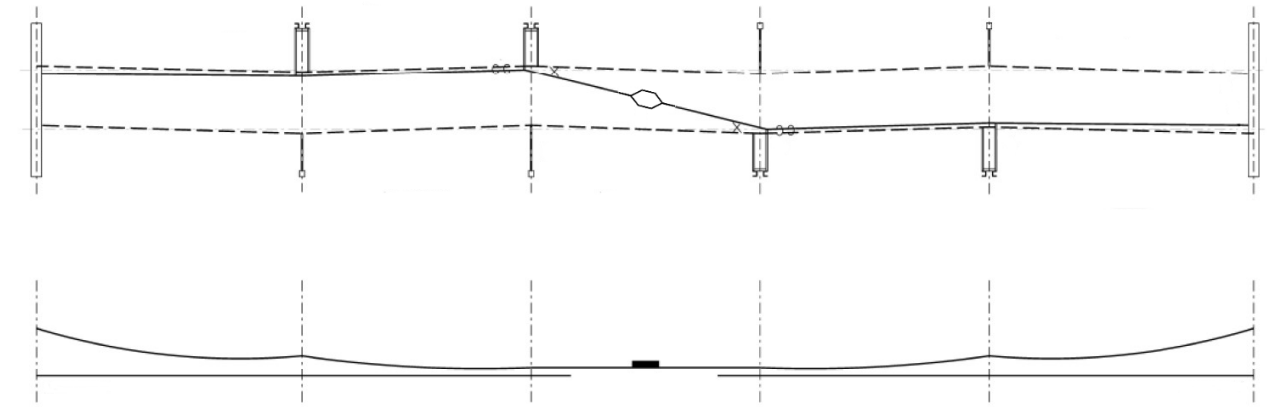


Figure 138: UKMS tangential wiring – plan and profile views[134];

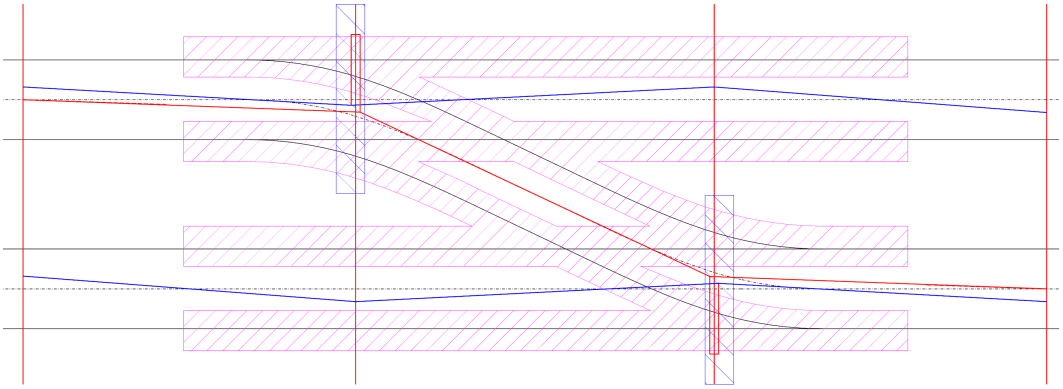


Figure 139: UKMS standard tangential geometry relative to fitting free zone for a 40mph Ev crossover[135];

The staggers in the above arrangement are positioned between the two track centrelines; this minimises hookover risk as a pantograph approaches the turnout in the trailing direction on either the through route or the crossover. Modern pantographs have sprung heads (section 11.1) and this feature is exploited by the wiring geometry; the stagger is such that the contact force pushes the side of the head near the incoming wire downwards, rolling the whole head (on a fixed head pantograph) or the carbon carrier only (on a floating head pantograph), and so moving the horn and/or wear strip away from the second wire.

[134] 141667-FAF-MAN-EOH-000002 "UK Master Series Allocation Design Manual"; Issue 1.8, 2017; Network Rail; fig. 13.2.

[135] Turnout staggers are +100/-100mm relative to relevant track, structure placed at 300mm toe opening. MS/B06/B01/A3 "Crossed Contacts Crossover General Arrangements"; Rev 01, 2017; Network Rail. Note that this drawing erroneously shows the staggers as -100/-100mm.

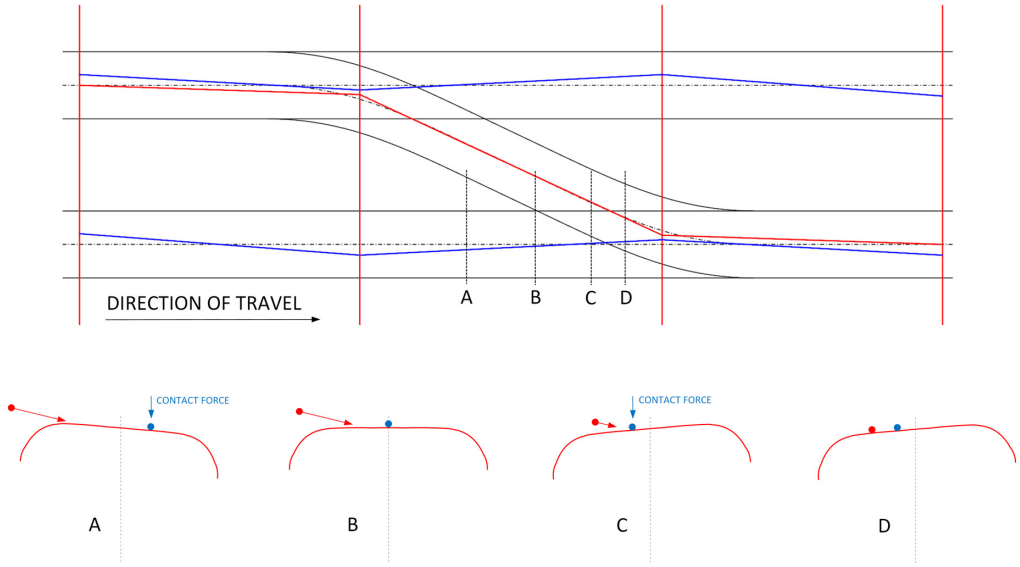


Figure 140: Pantograph approaching a turnout in the trailing direction, with head inclined away from the incoming wire (head angle exaggerated)

11.5.7. Cross-Droppered Method

Modern cross contact and tangential methods both use *cross droppering*. This entails droppering the mainline catenary to the crossover contact wire (and vice versa) in the vicinity of the turnout, to help both wire runs to rise and fall together as the pantograph passes. This system has been used in recent UK turnout wiring at speeds up to 200km/h.

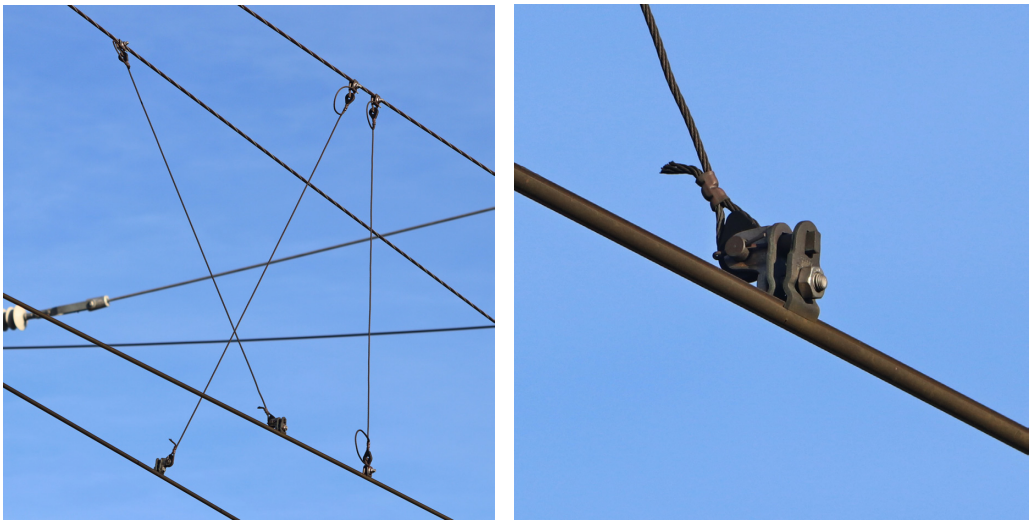


Figure 141: (l-r) Cross-droppering arrangement alongside normal dropper, inclined dropper clip showing offset thimble. Swindon, UK

It is not possible to use normal dropper clips for inclined droppering, as the inclination of the dropper would lead to twisting of the contact wire, and potential contact between the pantograph and the dropper clip; instead an *inclined dropper clip* is used, which has an offset fitting so that the load axis of the dropper intersects the contact wire, keeping the clip upright.

11.5.8. High Speed Three Wire System

All the systems described so far use a single wire run on the crossover itself. Since the running lines generally have separate electrical sections (section 10.3), this means a section insulator (section 11.6.1) is required at the midpoint of the crossover. Some high speed routes have high speed turnouts, where the dynamic performance

of a section insulator would be unacceptable.

They therefore use two wire runs on the crossover, allowing the use of an insulated overlap (section 11.4.2) on the crossover to achieve the necessary section break. At these speeds a smooth run-up and run-off of the pantograph between the wire runs is essential, and a number of different configurations are in use to achieve this. Some systems adopt a specific vertical profile for the middle of the three wire runs, meaning it acts as a guide wire and keeps a through-running pantograph out of contact with the inner third wire run. This improves dynamic performance and reduces hookover risk.

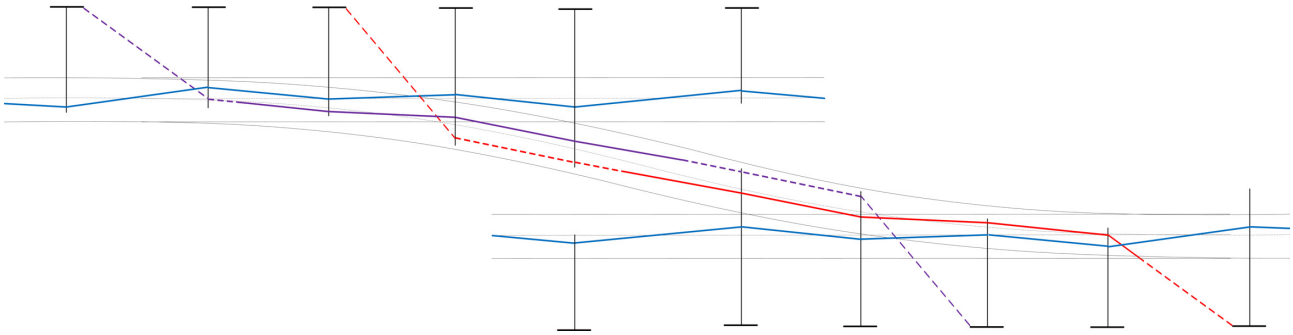


Figure 142: Typical high speed three wire crossover wiring

This means that a *triple cantilever* is needed at the control structure, and transfer is achieved by careful positioning of the three wires. This arrangement is not common in the UK, but is used on High Speed One and will be used on the future *High Speed Two* line.

Figure 143: High speed triple cantilever. Stratford, UK

11.6. Other Electrical Break Devices

11.6.1. Section Insulator

Although overlaps are used wherever possible to create section breaks, there are times when additional breaks are required for switching and sectioning at locations away from overlaps . At these locations, a *Section Insulator* (SI) is used. This is a set of insulators spliced into the contact wire and catenary, while

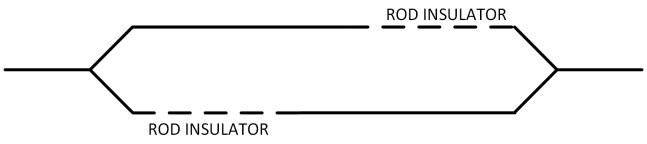


Figure 144: Plan view of typical skidless SI

allowing the pantograph to pass over it. A standard insulator is used in the catenary, while two options are available to carry the pantograph along the contact wire without loss of current collection; either an arrangement of skids is set below rod insulators (section 11.18) to form a *skidded SI*, or the rod insulators themselves carry the pantograph through the SI - a *skidless SI*. The latter is capable of higher speeds, being lower in weight, but the insulators require regular cleaning.

SIs are a significant hard spot in OLE, and for this reason their use is generally restricted to crossovers, sidings and station areas where speeds are lower. They should be supported at a structure wherever possible – if not, the droppers must be shortened locally to counteract the dead weight of the assembly. SIs are also difficult to set up, and there are more restrictive rules on horizontal position, depending on the width of the SI.

Figure 145: (l-r) SI types; Arthur Flury skidded, Arthur Flury skidless. Swindon and King's Cross, UK

11.6.2. Insulated Knuckles

Many historical systems have achieved electrical separation of adjacent wires in complex track layouts using an *insulated knuckle*. This takes the form of one or two insulators directly attached between two wire runs. Although electrically effective, the large and often unsupported mass means dynamic performance and contact wire wear is degraded. These assemblies are not used in modern systems.

Figure 146: Insulated knuckle. Southend, UK

11.6.3. Neutral Sections

An electrical break is required wherever different supply phases meet (section 10.1.3); or where there is a change of system voltage, as occurs at many European interfaces; or where an earthed section of operational OLE is to be provided at a location where sufficient electrical clearance (section 10.8) cannot be provided. At these locations a neutral section is used. This is a section of earthed OLE sandwiched between an insulator on either side. For AC systems fed from three phases with a phase angle of 120°, the total strength of the insulation between phases must be $\sqrt{3}$ x line voltage[136].

Neutral Sections are found at feeder stations and midpoint sectioning locations. The train must not draw power through the neutral section, since an arc would be drawn to earth. For this reason the train power is tripped off by a trackside *Automatic Power Controller* (APC) magnet, which operates the train's circuit breaker via a relay.

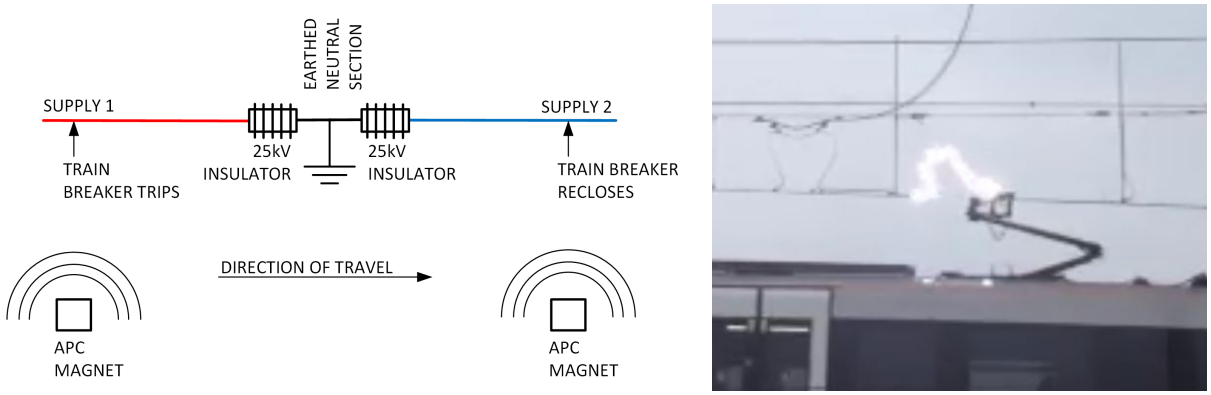


Figure 147: (l-r) Principle of a magnet-switched neutral section, arcing caused by missing APC magnet

Figure 148: APC magnets; Vortok type and traditional type. Witham, UK

When the train has cleared the neutral section, the circuit breaker is closed by a second APC magnet. For this reason care must be taken to place signals so that there is no risk of a train becoming stranded at a neutral section.

It is possible to eliminate the electrical arcing risk and the short-duration loss of power by adopting a *switched neutral section*. In this configuration the APC magnets are eliminated in favour of automated HV switching which is controlled by the signalling system, and enables the neutral section to be fed from either of the two traction supplies. The direction that the train approaches the neutral section will determine which of the two supplies is connected; once all pantographs are within the neutral section, the first supply is disconnected and then the second supply connected before the train leaves the neutral section.

[136] It is possible to reduce this potential difference somewhat by using specific patterns of three phase connections, as has been done on the Madrid-Seville line. "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p42.

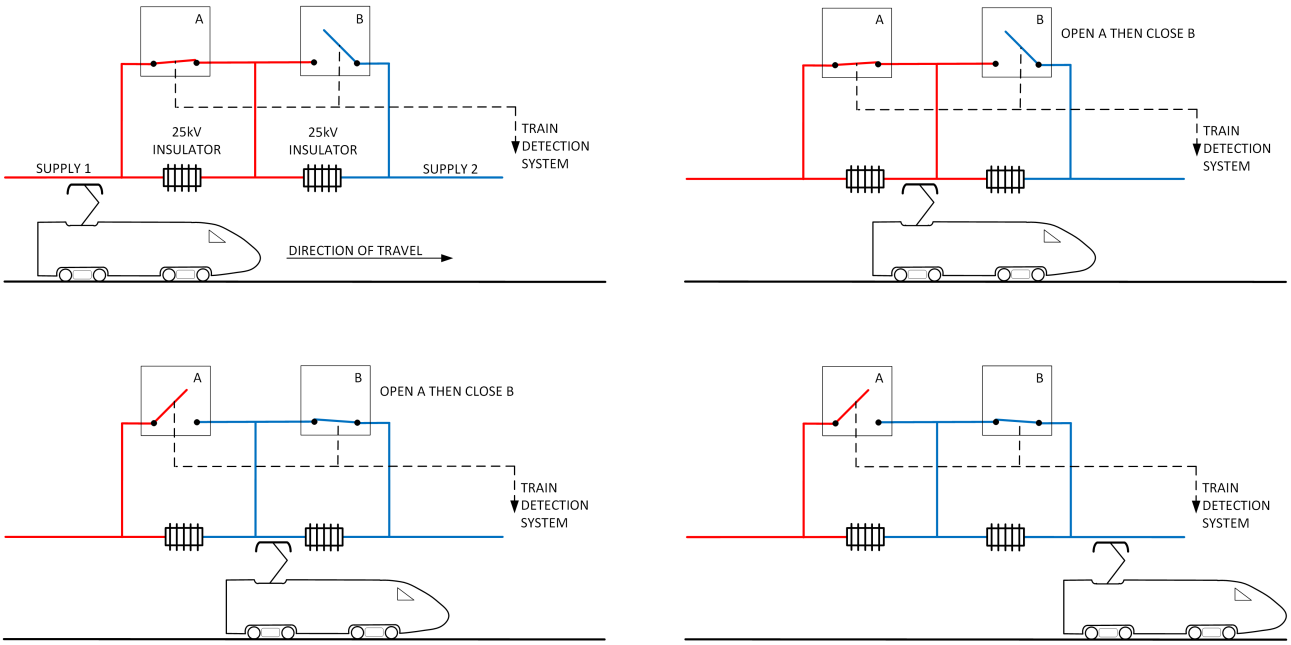


Figure 149: Principle of a signal-switched neutral section

This approach requires all pantographs to fit within the neutral section, and adds complexity in terms of HV switching and control. For these reasons it is not used in the UK.

In mechanical terms there are two types of neutral section; the *inline* type, and the *overlap* or *Carrier Wire Neutral Section* (CWNS) type.

The inline type consists either of glass bead insulators (over which a pantograph is able to run), or high speed section insulators, placed either side of the neutral point. Sacrificial *arcing horns* are often provided in the event that a train draws power through the earthed section. Inline neutral sections have been used on mainlines at up to 200km/h; however the geometry can be difficult to maintain, and the glass bead insulators require regular cleaning. Reliability problems in the UK have led to inline types being banned above 160km/h for new installations.

Figure 150: Arthur Flury type inline neutral section; note the uninsulated cantilever at the neutral point. Drayton Park, UK

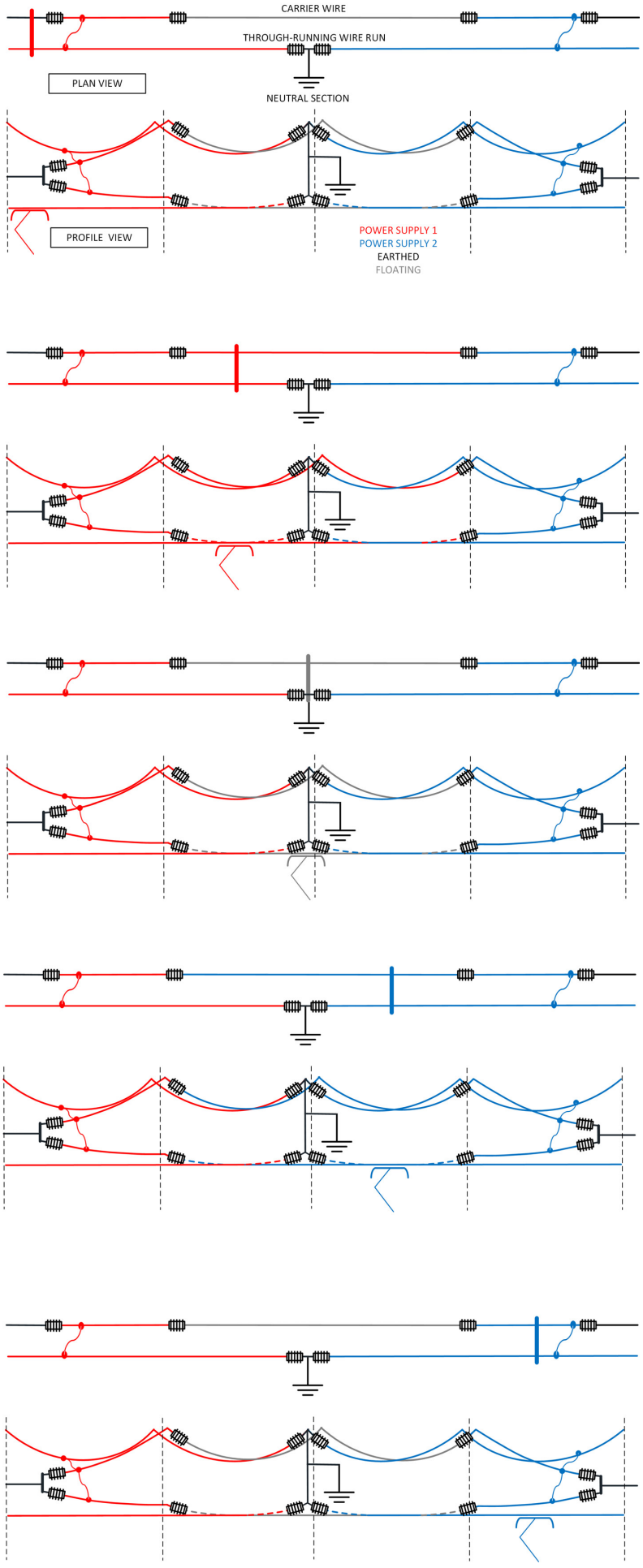


Figure 151: Transfer of a pantograph through a carrier wire neutral section

The carrier wire type consists of two or more overlaps in quick succession; the first transfers the pantograph from the first live wire run to an electrically floating wire run – the carrier wire; the second overlap transfers the pantograph back onto a second live wire run. Train power is switched off in the normal way. If the route carries trains with more than one pantograph, there are two ways of approaching the problem. If the multi-pantograph trains on the route have electrically common pans via an on-roof 25kV busbar, the CWNS must be made longer than the longest pantograph spacing. If the pans are not electrically common, then either the CWNS is made longer than the longest pantograph spacing, or is shorter than the shortest pantograph spacing.

Alternatively, the arrangement can be extended to three or four overlaps, as used in the UK. Either option must ensure that the incoming and outgoing wire runs are never connected through the carrier wire, pantographs and train busbar.

Carrier wire types can give better dynamic performance and reliability than the inline type, but require a more complex OLE arrangement and take up much more space. This can make it harder to find a location away from bridges, stations, junctions and signals, but still close to the switching site. Carrier wires were first used on European high speed lines and High Speed One, and are now being used in the UK on the GWML.

11.7. Isolators

OLE *isolators* provide a *point of isolation* in the traction circuit for the purposes of isolating sections or subsections of OLE (section 10.3) for planned or unplanned maintenance. They generally take the form of a horizontal or vertical throw *knife switch*, which when open provide a visible air gap between the supply and the OLE equivalent to at least Basic Insulation (section 10.8). In their simplest form they are not capable of making or breaking current, and so are only operated once the power supply has been disconnected at the circuit breaker (section 10.2.7). In this configuration the widely used term "switch" is not accurate, and they should correctly be referred to as isolators or *disconnectors*.

OLE isolators are typically mounted on the lineside, either on OLE masts also carrying support and registration equipment, or on standalone switching structures. Since the live elements are not insulated or screened, it is essential that the isolator is placed at sufficient height to minimise electric shock hazards.

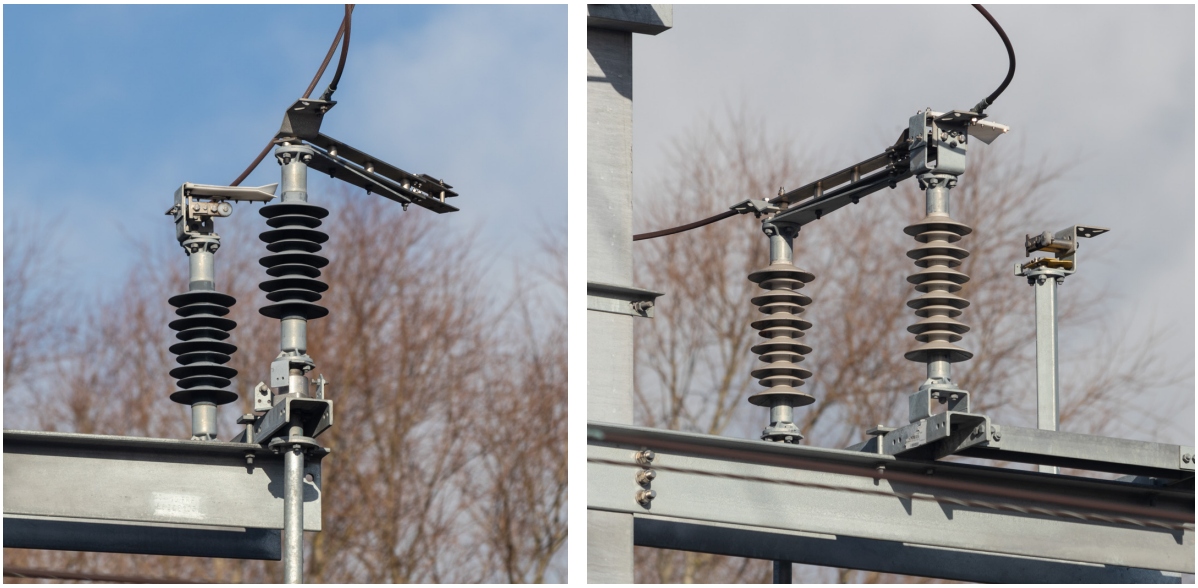


Figure 152: (l-r) MLE two-position non-load-break isolator in open position, MLE three-position closed/open/earth non-load-break isolator in closed position. Swindon, UK

Isolators can be either *two position* or *three position*. Two position isolators are either open or closed, and provide a simple point of isolation. Three position isolators have a second set of contacts, which can be used to:

- Provide an *alternate feed* path (closed/open/alternate closed) to allow another means to energise a subsection;
- Provide an earth connection (closed/open/earthed) to protect staff working on the OLE from inadvertent re-energisation (section 10.12.1) by the ECO making a mistake or by an electric train accidentally entering the isolated section;
- Earth a feed cable to allow it to be safely worked on (when used in the opposite orientation).

The knife blades and contacts are typically copper or silver-plated copper.

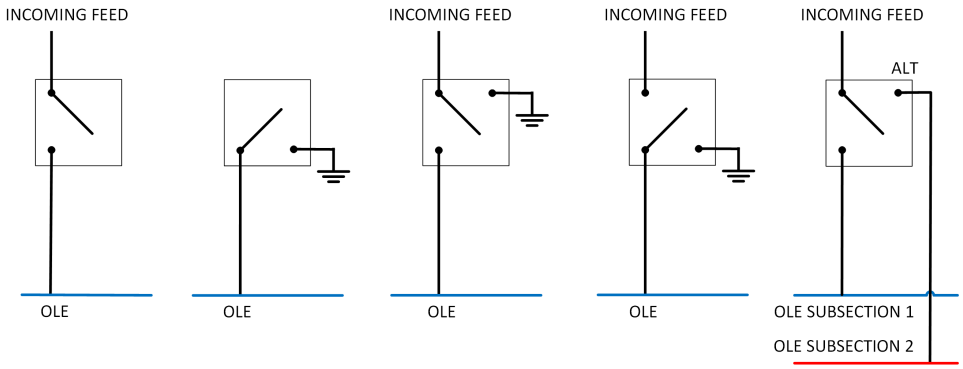


Figure 153: Isolator configurations (l-r) two-position closed/open, two-position open/earth OLE, three-position closed/open/earth incoming feed, three-position closed/open/earth OLE, three-position closed/open/alternate feed

Most isolators normally operate in the closed position – they are *Normally Closed* (N/C) – but some switches, such as those providing alternative feeds or an earthing facility, may be *Normally Open* (N/O).

OLE isolators can be manually operated or motor actuated. Manual isolators have a simple switch handle at the base of the mast. A padlocking arrangement is provided so that the isolator can be secured in the required position, and each isolator has a unique key which is held inside a locked key box. The key box is then locked with a generic key, and an authorised person can then operate the isolator as follows:

- Unlock key box and remove unique isolator key;
- Operate the isolator to the desired position and lock isolator;
- Remove the unique key and keep it with them, preventing inadvertent re-energisation until all staff are finished work.

Modern installations increasingly use a SCADA (section 10.7.3) operated *motor box* to provide rapid isolation by the electrical control operator.

Figure 154: (l-r) Actuators for torsion tube isolators; manual, motorised. Euston and Stoke Gifford, UK

Regardless of manual or motor actuation, the connection between the actuator and the switch assembly is either a *torsion tube* (for horizontal throw isolators), a *push rod* (for vertical throw isolators) or a *flexball drive*. Torsion tubes are the simplest to configure but can be prone to twist failures when actuated after a long unused period, during which the switch blade and jaws can become locked together through oxidisation. The flexball drive comprises a flexible hose filled with ball bearings; a piston at the drive end pushes the bearings further into the hose, and a piston at the isolator end translates that pressure into movement. This provides an easier installation set-up than the push-rod design.

Figure 155: (l-r) Rauscher & Stoecklin two position push-rod isolators in closed and open positions. Bushey, UK

Modern motorised isolators often have a method of remotely detecting that the isolator blade is secured in the correct position, since the security of the isolation depends on it, and the integrity of the rod mechanism cannot be taken for granted. These isolators have a *reliable indication* microswitch fitted to the base of the isolator pivoting insulator itself, which detects the switch position and reports it back via the SCADA system.

Figure 156: Reliable indication microswitch (arrowed). Didcot, UK

Some isolators are required to break load current (section 10.1.2) so that they can safely be operated without first disconnecting the power supply – these can be properly described as *load break switches*. In this case there must be a means of extinguishing the electrical arc that will otherwise form as the isolator contacts move apart.

Figure 157: (l-r) MLE three position load-break isolator in the open position, and in the closed position. Earth position at rear, vacuum interrupter bottle at front

This is achieved by attaching a *vacuum interrupter* to the isolator. As the isolator path is broken, the traction current instead follows the path of least resistance through a vacuum bottle, which contains a pair of contacts. After the isolator contacts are safely open, the interrupter contacts are then opened by the actuator, and no arc is able to be struck in the vacuum.

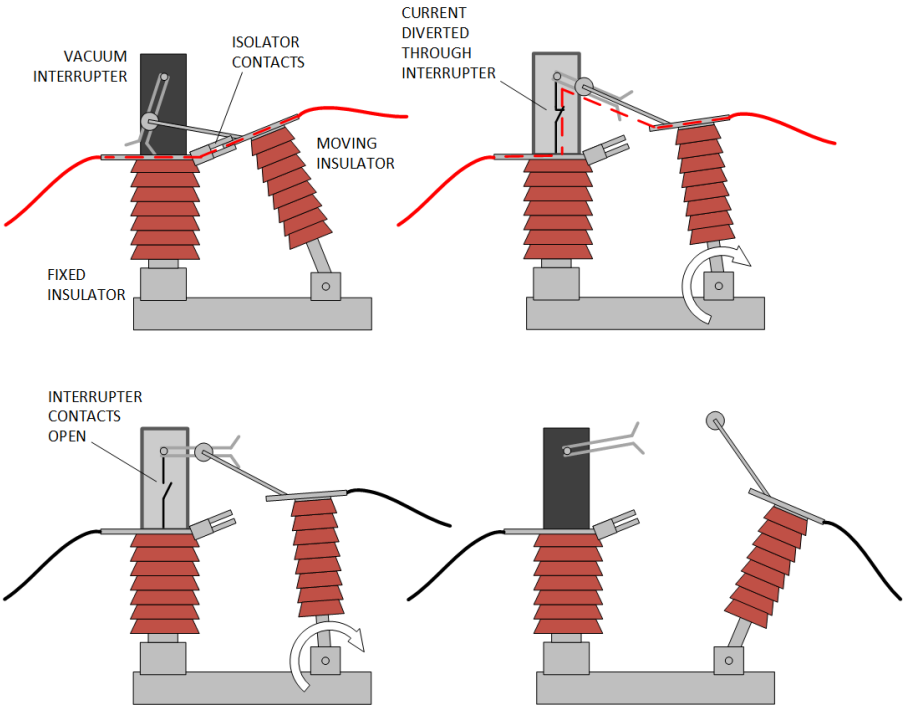


Figure 158: Operation of vacuum bottle load-break switch (current flow shown in red)

Figure 159: Driescher load-break two position isolators. Magor, UK

11.7.1. Circuit Main Earths

OLE systems in the UK are now applying the concept taken from the Electricity Supply Industry - that of the *Circuit Main Earth* (CME). This is an arrangement which will discharge electrical energy to earth in the event of an inadvertent re-energisation (section 10.12.1) of equipment which has been disconnected from its power supply in order to carry out maintenance or repair work.

Figure 160: (l-r) MLE non-load-break isolator with flexball actuation (arrowed) performing the function of a CME, detail on flexball actuator. Bristol Parkway, UK

The CME may be provided either by use of portable earths at a DEP location (section 10.12.1), or increasingly by using a device – typically a motorised two-position (open/earth) isolator with load-break capability. In either case the location must be coincident with a high-integrity cross-bond location (section 10.10.1) to ensure that energy is properly discharged to earth, and within a short distance[137] of the location at which the re-energisation could occur.

11.7.2. Feeding Arrangements

The options available for connecting an isolator to the OLE depend on the track configuration. Where the OLE is immediately adjacent to the isolator, a feed wire is run direct to the catenary and contact wire. However, this is not an option where the feed needs to cross other wire runs to reach its connection point.

Figure 161: Candlestick bare feeds along portal boom. Rugby, UK

In this situation three options are available. The first is to use a *candlestick* feed arrangement, where a bare feed is run above a suitable portal or TTC boom (section 11.10) using a series of insulators on *stovepipes*. This

[137] In the UK, CMEs must be within 90m of the point of inadvertent re-energisation.

arrangement has one significant disadvantage; when the wire runs below it are isolated, the live equipment above staff forms a residual hazard (section 17.12). This is often mitigated by lengthening the stovepipes to move the hazard further from the wire runs.

An alternative is to use a *spanwire feed structure*. This arrangement uses freely suspended wires slung between tall lineside masts. Feed wires then run down to the connected wire run. These allow the live parts to be placed higher up, thus reducing the residual hazard. It is also increasingly common to use separate structures rather than the structures used for support and registration, moving the residual hazard away from the location most frequently visited by maintenance staff during an isolation.

Figure 162: Spanwire feed structures. Bushey, UK

The final option (which completely removes the residual hazard) can be applied only if the isolator is switching one track only across a section insulator (section 11.6.1) or insulated overlap (section 11.4.2). In this case the isolator can be placed directly over the related wire run(s), on a suitable portal or TTC boom. Actuation of the isolator is achieved by means of push-rods which run in rollers along the boom from the mast to the isolator, or a flexible ball drive.

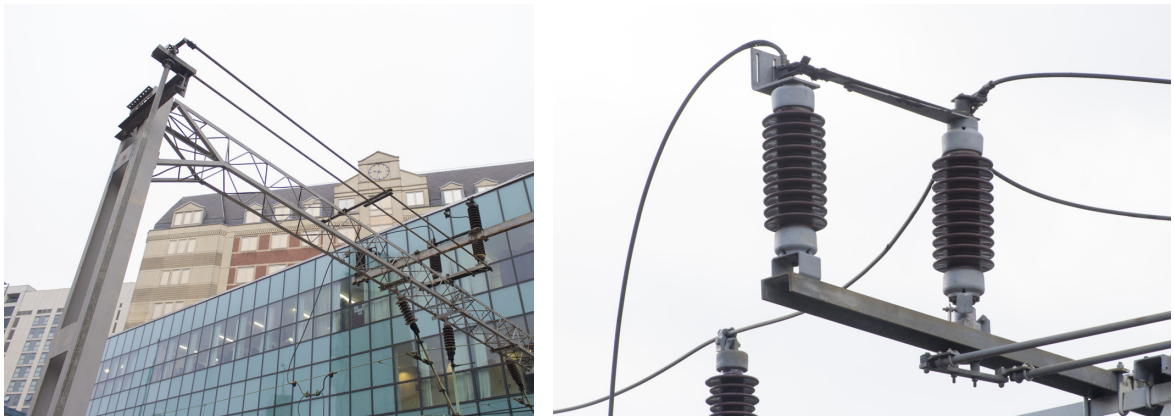


Figure 163: (l-r) Push-rod switch actuation, MLE 2-position push-rod actuated switch. Euston and Birmingham, UK

A single push-pull rod (known as a *pear drive*) is now favoured over twin rods in the UK, as this arrangement is easier to set up and does not unevenly load the rods.

11.8. Mechanical Clearances

It is essential to maintain mechanical clearances between static live parts of the system, and those parts which move. Key mechanical clearances are:

- Pantograph (section 11.1) to registration arm (section 11.13.2);
- Pantograph to drop bracket;
- Registration arm to supporting assembly;
- Insulated pantograph horn to bridge arch.

Typical mechanical clearances are 15mm for pantograph to registration arm, and 80mm for live pantograph to all other live parts.

11.9. OLE Structure Loadings

All OLE structures must be capable of withstanding a number of loads:

- *Permanent actions* (also known as *dead loads*) in the system caused by equipment weight and tension;
- *Variable actions* (also known as *live loads*).

Variable actions may be further subdivided into:

- *Environmental loads*, created by the action of wind and weight of ice and snow;
- *Accidental loads* caused by a dewirement or other temporary situation;
- *Construction loads*, caused by the extra weight of staff working on the structure, or unbalanced loads caused by partial installation of equipment.

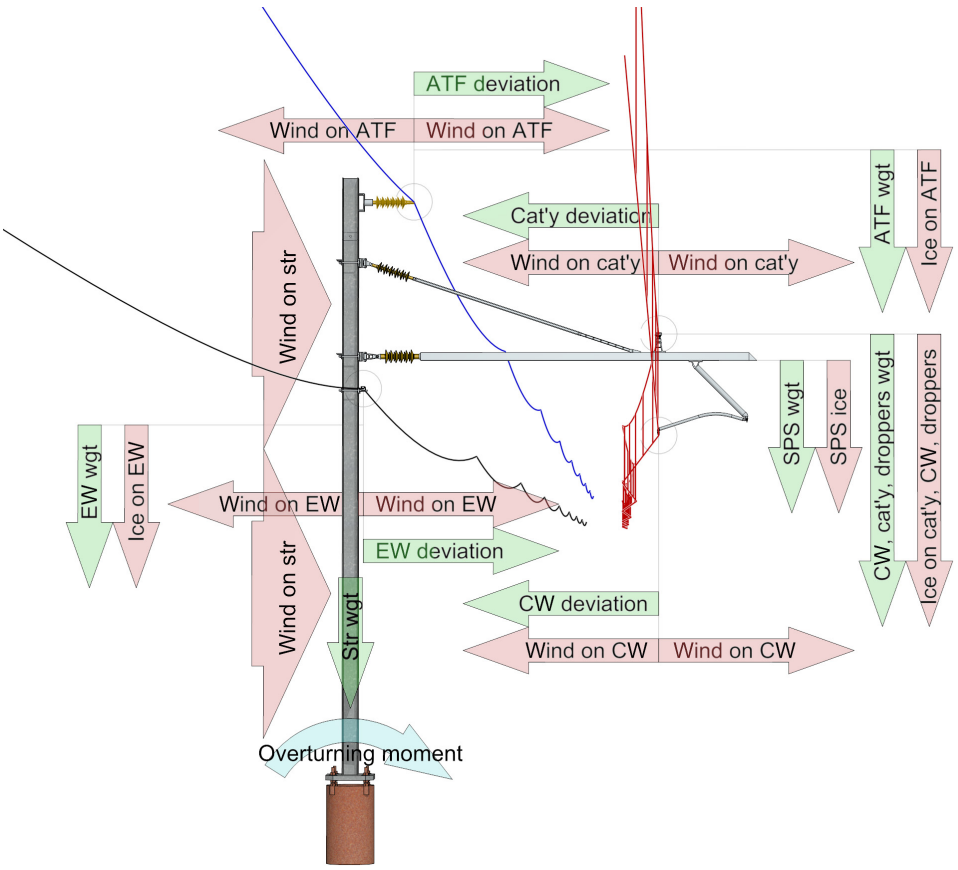


Figure 164: Mechanical loads in the cross-track direction on a typical cantilever structure[138]

These *load cases* must be calculated, *partial factors* (factors of safety) applied to each, and then combined into a set of *load case combinations* which describe the loads experienced under different conditions. For instance, in the UK maximum wind is unlikely to be experienced at the same time as maximum ice, so the low temperature load case combination applies a reduced wind load. Windspeeds are calculated based on a regional statistically-determined windspeed, modified by the shielding or exposure of the local terrain.

The load case combinations are compared with the *Ultimate Limit State* (*ULS*) of the structure – that is, the point of mechanical failure. Each load case combination must be less than the ULS – if it is not, then either the design is changed to reduce the loads, or the steelwork size increased. Structure loads that are checked include normal force (compression/tension), *biaxial shear*, *biaxial moment* and *torsion*. Shear loads and torsion are generally much lower than their ULS capacities, and so structural checks are usually undertaken for the interaction between axial load and biaxial moments for each individual load combination.

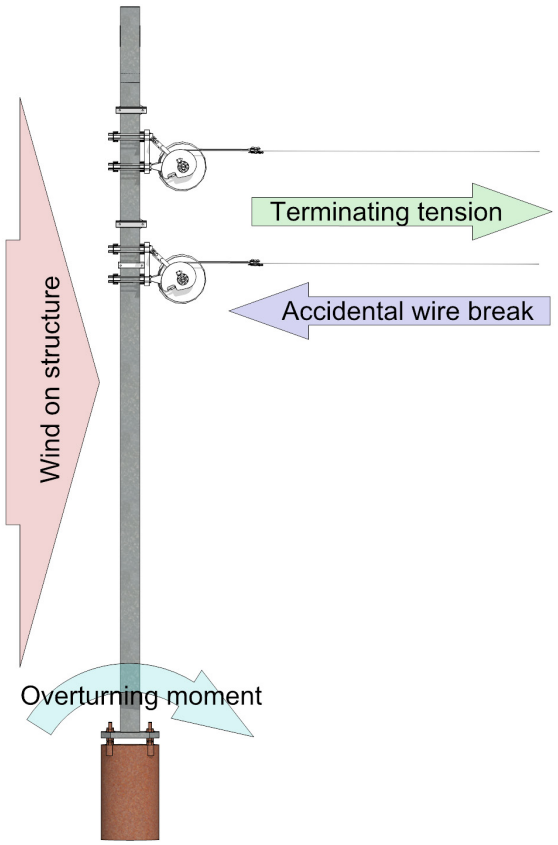


Figure 165: Mechanical loads in along-track direction on a typical anchor structure[139]

Figure 166: Lateral torsional buckling of an I-beam cantilever mast due to additional load of tree falling on OLE in high winds. East Anglia, UK

ULS checks ensure that the structure will not fail, but more stringent limits are needed to ensure that the OLE performance is not compromised by less onerous environmental conditions. This is done by calculating the *Serviceability Limit State* (*SLS*), which is the level of loading needed to deflect the structure to the point that OLE geometry is compromised. Most OLE systems have across-track and vertical deflection limits. SLS tests use lower factors of safety, to reflect the lower risks involved.

The most common form of OLE structural failure is long-term foundation (section 11.11) movement, driven by the *overturning moment* at the base of the mast; this is easy to detect and can be controlled by height and stagger adjustment and/or structure support measures.

Main steelwork generally only fails due to accidental impact; the failure mode will depend on the steel

[138] Dead loads are green, live loads are red.

[139] Dead loads are green, live loads are red, relieving loads are purple.

section used. For instance, the key failure mode for an I-beam structure is known as *lateral torsional buckling*. This is induced by a moment acting in the direction of the stronger axis, and occurs in structures where the major axis stiffness is far higher than that of the minor axis.

The permanent loads on a cantilever structure will lead to a certain amount of *elastic deflection* of the mast. Depending on the loads and mast capacity, this may be large enough to be visible to train drivers. While not unsafe, this can be unsettling for drivers, and so in the UK it is normal[140] to apply *mast rake* using the foundation holding down bolts (section 11.11.2) to lean the mast between ½° and 1° away from the track in the unloaded condition.

11.9.1. Wind Loadings

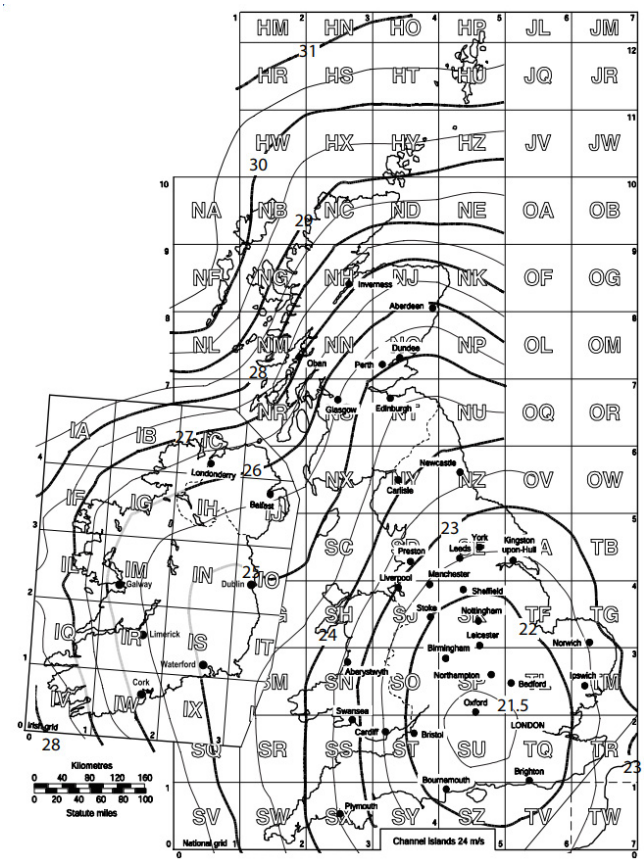


Figure 167: UK isocline map of base windspeeds for wind loading calculations[141]

ULS wind loads are typically calculated based on a 1 in 50 year return period; that is, the maximum 10 minute mean windspeed which statistics show will not be exceeded over a 50 year period. For SLS checks a 3 year return period is generally used, to reflect the lower risk (and unlikelihood of running trains during a 1-in-50 year storm).

This *base windspeed* is modified by factors reflecting the local topography, to give the *design windspeed* or *design wind pressure* which is used in all wind loading calculations. Wind forces will bear on both the structure itself, and the wires which are attached to it.

11.9.2. Ice Loadings

The level of ice loading to be used is determined by the climate in which the system operates; in the UK, radial thicknesses between 3.5mm and 9.5mm are used, depending on location and risk factors.

[140] UKMS drawing MS/B98/K07/A3 "Rake Instructions for Masts"; Rev 00, 27 March 2017; Network Rail.

[141] UK National Annex to BS EN1991-1-4:2005+A1:2010 "UK National Annex to Eurocode 1 - Actions on structures; Part 1-4: General actions - Wind actions"; January 2011; BSI; figure NA.1.

Figure 168: Extreme ice conditions; icicles being removed from Ipswich Tunnel, UK

11.10. OLE Structures

OLE structures play an electrical as well as mechanical role. Mechanically, they must hold the wires at their design positions under a range of environmental conditions, and keep deflections under wind within specified limits. Electrically, they must be capable of withstanding the *mechanical stress* and *thermal stress* caused by voltage and current surges under fault conditions.

Figure 169: Precast concrete masts. Perth, Australia

For AC systems, the structures and their foundations also form a distributed earth system (section 10.10.1), and they must be electrically continuous so that fault currents can pass freely to general mass of earth in the event of an insulator failure. This means that structures are generally formed from galvanised steel (or in some cases, weathering steel), although painted steel structures were widely used historically. Some administrations

outside the UK have made extensive use of concrete; although the weight of these can cause constructability issues, and their form of construction is problematic for earthing and bonding when used in AC systems.

For steel masts, the form that the mast takes is largely a matter of local preference and the relative cost of hot rolled steel sections versus welded fabrication of a lattice structure. Using rolled steel gives the advantage of a ready-made section that requires little fabrication other than the welding of a *baseplate*; whereas a lattice structure reduces the amount of steel used, but requires increased workshop time and the availability of a skilled welding workforce. For DC systems, stray currents (section 10.10.2) mean structures must be insulated from earth, and therefore non-conductive materials may be considered.

Historic and current standards in each administration give rise to a set of standard *steel sections*. Most systems use standard structure designs which are held in Basic Design Ranges (section 13.1). These designs are pre-approved for use in appropriate locations.

OLE geometry is controlled at structures in two ways; *supporting* the OLE means fixing the vertical position. This is usually done at the catenary, by means of a clamp, link or pulley (section 11.3); the contact wire vertical restraint is via the droppers suspended from the catenary. A structure may also be used to *register* the OLE; that is, to fix the horizontal position. This is done at the catenary, as above; and at the contact wire, by means of a registration arm (section 11.13.2). This is free to move vertically to take account of uplift. Structures for auto tensioned systems also have to allow for along-track movement (section 11.3).

It is sometimes necessary to use a structure for support only (for instance to support the mass of an SI), or to register only (to get a wire run around a heavy curve). These structures are designated as *Not Registered* (NR) or *Not Supported* (NS). Sometimes a wire run may not need any direct connection to a structure and will pass through – for instance a switching structure carrying a feed onto the OLE; these are designated as *Not Supported or Registered* (NSR).

There are many different types of OLE structure, each appropriate to a particular use.

11.10.1. Single Cantilever

The *single cantilever* is the basic building block of most OLE systems. It is designed to support one wire run over one track.

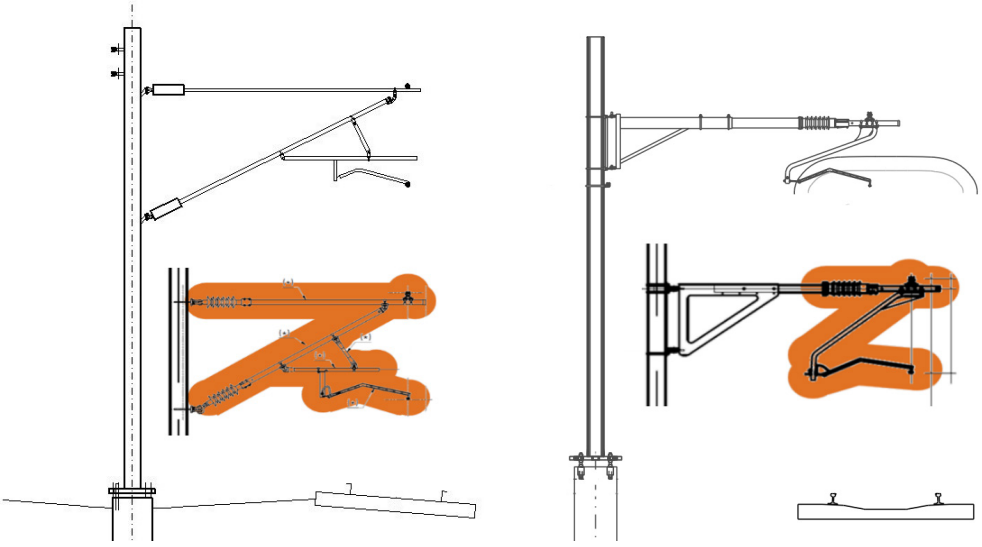


Figure 170: (l-r) Traditional single cantilever, and Series 1 equivalent with live envelopes shown (insets)

The single cantilever is cheap, easy to construct and adjust, and is the standard structure for use on a two track

railway. Efficiently designed railways maximise the use of these structures.

The traditional cantilever shown above left has a large electrically live envelope, and is awkward to construct due to the use of sloping tubes. Recently in the UK cantilevers have been used which have a much smaller electrical envelope (above right) and a rapid adjustment mechanism, so that construction time is minimised and staff safety maximised.

11.10.2. Double Cantilever

Figure 171: Typical double cantilever. Edgbaston, UK

It is often necessary, particularly at crossovers and overlaps, to support two wire runs over one track. The simplest way to do this is by means of a *double cantilever*.

The two cantilever arms are separated along track on horizontal spreader channels to allow for along-track movement (section 11.3) without the equipments clashing. Some high speed railways place an overlap on crossovers to avoid using an SI (section 11.6.1), and these systems use a triple cantilever (section 11.5.8) on the same principal as the double cantilever.

The double cantilever illustrates the important principal of *Mechanically Independent Registration* (MIR). This means that each wire run has a support and registration which is independent of any other. In the event of one wire run being damaged, the other should continue to operate within geometrical limits. This has important implications for OLE availability in the event of a dewirement.

11.10.3. Back to Back Cantilever

Where there is sufficient clearance between two tracks , a *back to back cantilever* may be used to support wire runs over two tracks.

This has the advantage of requiring less materials than a pair of single cantilevers.

However, maintenance access is more difficult if traditional cantilevers are used, since the live equipment on one track must be isolated in order to work on the second track, meaning the railway is closed to electric services. This arrangement can also cause problems with signal sighting (section 16.7.1) but is often used in tram systems to improve aesthetics and reduce land-take.

Figure 172: Typical back to back cantilever. Rugby

11.10.4. Two Track Cantilever

Figure 173: Typical spanwire two track cantilever. Egbaston, UK

It is often the case that foundation space is only available on one side of a two track railway; either due to a physical obstruction such as signalling equipment, or because signal or level crossing sighting (section 16.11) requires a clear sight line on the other side. In this case, the *Two Track Cantilever* (TTC) is used to support several equipments over two tracks.

Pairs of TTCs can also be used to aid construction on a four track railway where all-lines closure for portal installation (section 19.6) is not practical.

The TTC will experience a higher overturning moment (section 11.9) at the base of the mast, and for this reason the foundation will be larger to resist the moment. TTCs are usually used only where single cantilevers or portals are not suitable.

TTCs can be provided with MIRs, with wire runs on separate cantilevers; or can be configured to use a cross span wire strung between the TTC mast and a *nose* assembly at the extremity of the TTC boom. In this configuration the TTC will not be mechanically independent.

11.10.5. Flying Tail Structures

On heavy curves and complex junctions it is sometimes necessary to register the OLE without supporting it, to maintain horizontal geometry. These Not Supported structures are known as *flying tail* structures.

Figure 174: Flying tail structures registering tram OLE around a tight curve. Manchester, UK

11.10.6. Portals

For railways with more than two tracks, it is not generally possible to use single cantilevers as there is insufficient space between tracks. For this reason the standard structure for a multi-track railway is the *portal*.

Figure 175: Two track mark 1 portal structure. Tring, UK

The structure shown has MIRs, and in this configuration it is relatively easy to make adjustments on the structure; however construction or demolition requires a *possession* (closure) of the railway, and *isolation and earthing* of all OLE. The use of a crane, along with good access, is also necessary. For this reason, feasibility of construction must be considered when designing with portals. Portals can also be provided with spanwires.

Figure 176: (l-r) Hinge-based portal, hinge-based portal connection on viaduct. Selly Oak and Glasgow, UK

A portal may be either a *fixed* or *hinged* type. The fixed type has rigid bolted *moment connections* at each foundation and at each corner; this means all structure loads are transferred to the foundation.

A hinged or pinned portal will have one or two *hinge pin* connections, either at the foundations or at the connections between the mast and boom.

With this arrangement, only the vertical and shear component of the across-track loads are transferred to the foundation – an arrangement which is especially useful on older viaducts, which may not be capable of withstanding overturning moments, or may have limitations on intrusive works due to their heritage status. Along-track loads are unaffected.

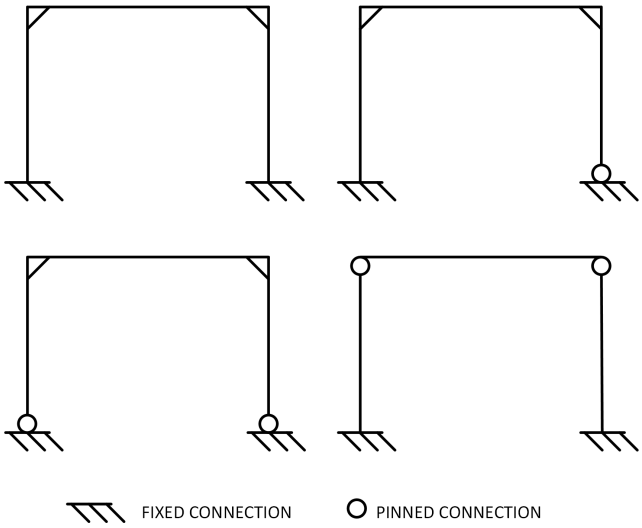


Figure 177: (clockwise from top left) Portal configurations; fully fixed, single pin base, pinned boom, double pin base[142]

11.10.7. Headspans

An alternative to the portal in multi-track areas is the *headspan* structure. This structure comprises two extended masts, with two horizontal tensioned wires (the *upper cross span* and *lower cross span* wires) strung between them to locate the OLE. A third top wire is a profiled *headspan wire*, and this provides support to the overall arrangement.

The headspan has the advantage of being cheaper and easier to install than the equivalent portal. However the headspan is a load-balanced system, where the tensions in the wire runs themselves contribute to the geometric stability. If a wire run breaks, the design geometry will be lost since all other wire runs will be out of balance. This type of structure is therefore not mechanically independent, and a failure means all tracks are out of service. Headspans require regular maintenance to check the span wire tensions, and adjustment of the equipment tends to trigger design and replacement of assemblies. For high speed lines, the mechanical wave created by the passage of a train can also affect adjacent wire runs. Headspans also require larger foundations than portals, to resist the high overturning moments (section 11.9) caused by the headspan tension, and this can cause problems in areas of poor ground. Wire corrosion problems have also been experienced in the UK.

UK-pattern headspans use an inclined tube between the upper and lower span wires – unlike many European patterns. This provides resistance to the twist forces which the radial loads would otherwise impart onto the span wires, as well as a connection point for the registration arm (section 11.13.2). UK headspans have no temperature compensation on the span wires, but some overseas systems use a spring tensioner to maintain a quasi-constant tension.

[142] Note that the pinned boom retains an element of moment transfer into the foundation.

Figure 178: Typical two track headspan. South Hylton

Because of the reliability issues, headspans are best suited to lower speed applications or applications where low capital cost is more important than high availability or performance. In the UK headspans have historically been installed in large numbers; however their poor performance means they are not used for new designs on mainlines.

Figure 179: Electrified platforms using headspans in Span 4, Paddington – a Grade 1 listed station with OLE almost invisible

Headspans are however a good solution to the problem of visual intrusion at sensitive sites such as listed stations; with intelligent design and use of rod insulators, these structures can come close to invisibility.

11.10.8. Spanwire Portals

A compromise can be struck between the performance advantage of a portal and the cost advantage of a headspan, by using a spanwire portal. This uses a portal boom but with a spanwire to fix the registration equipment, thus avoiding expensive stovepipe arrangements. This is not an MIR arrangement, and is generally confined to sidings or complex areas.

Figure 180: Typical spanwire portal. Kentish Town, UK

11.10.9. Bridge Supports

Wherever possible, OLE passes through bridges without being connected to them. These bridges are *free running*. Where low headroom or long width makes it impossible to achieve this, it is necessary to attach one or more support and/or registration assemblies to the bridge. This type of OLE arrangement is known as a *fitted bridge*. Fitting can be done in a number of ways, depending on the type of bridge and the clearance restrictions.

Figure 181: Glass fibre claw-ended bridge arm (insulator in white). Whitecraigs, UK

Many bridges have flat decks constructed of iron, steel or concrete , and these can pose a problem if the bridge was not designed to take account of OLE clearances. In this case a *glass fibre bridge arm* can be used. The arm both supports and registers the OLE. The insulator material has some flexibility, and this provides for a reduced amount of uplift to assist with clearances. Thus the OLE is both supported, but also held down, by the arm. Various end fittings are available; a *claw-ended* arm provides support for a contenary (section 10.8) with a small system height and a live fitting, and a *stress-graded* arm for twin contact equipment (section 11.13.1) provides a specially shaped live fitting which minimises the electrical stress at the live point closest to the bridge, to help prevent flashover. More recently *insulated head* arms (see figure 73 for an example) have been used where the whole head is covered with an insulated coating, to further reduce flashover risk.

Figure 182: Glass fibre stress-graded bridge arm; note the dome shape of the end fitting. Perry Barr, UK

11.10.10. Terminating Anchors

Anchors are required wherever a wire run is terminated. They must be capable of withstanding the overturning moment created by the tension in the contact wire and catenary, both under normal operation and in the event of a wire breakage.

Terminating Anchors take a variety of forms. A stand-alone anchor structure may be used, although wherever possible an existing cantilever, TTC, headspan or portal mast is used to keep steelwork costs down.

An anchor structure may be *self-supporting*; that is, the steel section and the foundation withstand the entire overturning moment; or it may use a *compression strut* on the same side of the anchor as the terminations; or it may be *back-tied*, where a tensioned tie wire or rod extends from the top of the structure down to a mass foundation at a short distance from the structure.

The back-tied type has the advantage that a significant portion of the tension load is transferred to the mass foundation, and so the steel section and main foundation size can be reduced. The self-supporting type is used where there is no space for a back-tie. Terminating anchors can carry balance weights, spring tensioners (section 11.3) or fixed anchors.

It is often necessary to terminate a series of wire runs at the end of a set of sidings; in this situation, using individual masts would be inefficient and provide a collision risk for any train which overruns the buffer stop. For this reason a *goalpost anchor* is generally used.

Figure 183: (l-r) UK1 Siemens back-tied anti-fall balance weight anchor, self-supporting fixed anchor. Rugby and Glasgow, UK

Figure 184: Tensorex spiral torsion spring tensioners. Lower Basildon, UK

Figure 185: Goalpost anchor. Birmingham, UK

11.10.11. Midpoint Anchors

Full auto tension lengths (section 11.3) require the use of a midpoint anchor to constrain the tension length and prevent along-track migration. The arrangement of a midpoint anchor depends on the type of structures in use. For cantilevers, the MPA is arranged by means of a tie wire which is clamped to the catenary. This wire is terminated at the structure either side to form the restraint.

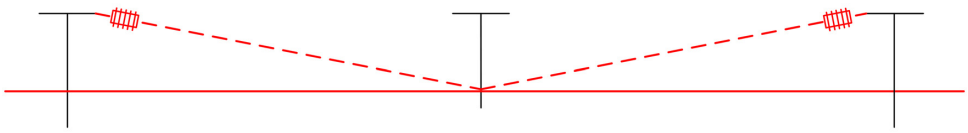


Figure 186: Tie-wire MPA arrangement for cantilevers

For portals, a direct connection to the portal boom via insulators is generally used. The connection is jumpered to maintain electrical continuity, and a *z-dropper* may be provided to additionally restrain the contact wire.

Figure 187: Typical MPA arrangement for portals with catenary jumper and z-dropper. Cholsey, UK

For headspans, the MPA cannot be a single point restraint due to the flexible nature of the system. Therefore a *distributed MPA* is used; the catenary is clamped to the upper cross span wire over several structures to distribute the load.

11.11. OLE Foundations

OLE foundations play a similar dual electrical-mechanical role to OLE structures; the foundation must withstand the mechanical loads, but also facilitate the flow of fault current to general mass of earth for AC systems (section 10.10.1), or (ideally) assist in preventing it for DC systems (section 10.10.2).

The main component of mechanical load on an OLE foundation is the overturning moment at the base of the mast (section 11.9). This determines the configuration of the foundation, and there are a number of different types, each designed to resist this moment. The type of foundation chosen must be matched to the ground conditions, ground profile and construction methodology (section 19.4).

11.11.1. Planted Mast Foundations

Planted Mast Foundations are formed by setting a polystyrene former into a previously dug hole, pouring concrete around the former, and then inserting reinforcing steel into the wet concrete. The former is then burned away, and an extended mast placed into the foundation and grouted. Although extensively used in early OLE systems, they are no longer favoured when electrifying operational railways, due to the requirement to support the mast while the foundation is *curing*, the safety risks of excavating deep holes, and the use of chemicals in burning away the former. A modern form of planted mast is however used on greenfield railways, notably for high speed lines (section 9.5) where access is less restrictive.

Figure 188: Planted mast. Stevenage, UK

11.11.2. Side Bearing Concrete Foundations

A *side bearing concrete* foundation comprises a cuboid of reinforced concrete, with the long side arranged vertically. The overturning moment is resisted by this long side bearing on the surrounding ground.

Figure 189: (l-r) Bolted side bearing concrete foundation, clamped side bearing concrete foundation. Stratford, UK

A hole is dug, a reinforced steel cage placed in the hole, the foundation poured, and a dressed concrete cap incorporating *holding down bolts* poured on top of the main foundation. The holding down bolts protrude from the cap, and a *bolted base* mast is clamped between upper and lower nuts to allow for adjustment of mast verticality.

A variant of this design, used for more highly loaded masts, is to clamp the mast baseplate directly to the concrete cap. This has the advantage of removing the bending forces on the bolts, but means that no verticality adjustment is available. Accuracy of concrete levelling is essential for this type of foundation.

Side bearing foundations are favoured for level ground with a high *bearing pressure* and good access for appropriate plant.

11.11.3. Mass Concrete Foundations

These are used to attach back-ties for anchor structures. They comprise a cuboid of reinforced concrete dug into the ground; an attachment point is provided for terminating the back-tie.

Figure 190: Mass concrete back-tie foundation. Peterborough, UK

11.11.4. Piled Foundations

Modern piling techniques offer a number of solutions, which are generally used where either ground conditions are poor, or access time is limited.

Like the side bearing concrete foundation, the moment is resisted by the long side of the pile bearing against the surrounding ground. All the types of pile detailed below, with the exception of the driven steel type, have a dressed concrete cap added after piling, to give controlled water runoff and to take the holding down bolts for a bolted base mast.

Figure 191: Augered pile foundation. Stoke Gifford, UK

A *bored pile* foundation consists of a reinforced concrete cylinder similar to the side bearing type. A boring rig is used to dig the hole in stages, and concrete is poured onto a reinforced steel cage placed in the hole. This piling method is only suitable for good ground, since the hole has a tendency to collapse before the concrete can be poured.

An *augered pile* (or to give its full name, *continuous flight augered pile*) is similar to a bored pile, except that the hole is created in one operation; after having placed a short steel sleeve into the ground, a hole is augered down through the sleeve. As the auger is withdrawn, concrete is pumped down the hollow shaft of the auger and into the hole from the bottom upward. A reinforced steel cage is placed into the concrete before it cures. This avoids the problem of hole collapse.

A *driven concrete* pile consists of a precast reinforced concrete pile, which is driven into the ground by a series of blows from a piling rig. These are particularly suited to soft ground.

A *driven steel tube pile* uses the same installation technique as the driven concrete type, but the pile is a hollow steel cylinder. This makes it much easier to drive, and allows driving of long piles in sections, as each can be bolted on as the previous section reaches ground level. The holding down bolts are pre-welded into the top of the pile, making it an attractive proposition for rapid installation. The disadvantage is that the steel can corrode if placed in acidic ground conditions without suitable protection.

Figure 192: Driven steel tube pile. Iver, UK

Unlike other foundation types, the steel tube has no bottom to bear on the ground below it, and so relies on *skin friction* to withstand vertical loads. This can make it less effective for heavily loaded anchor portals where the anchor forces bear down on the foundation.

The *screw pile* comprises a self-driving bore which forms the foundation itself; it is screwed into the ground, and the pile cap or steel grillage added.

11.11.5. Gravity Foundations

Figure 193: Combined gravity foundation for mast and back-tie on viaduct. Fenchurch Street, UK

A *gravity foundation* (also known as a *gravity pad*) takes the form of a shallow cuboid of reinforced concrete, arranged to form a large footprint. The pad is dug a short way into the ground; the moment is resisted by the underside of the pad bearing against the ground below it on the compression side, and the mass of the foundation on the tension side.

Gravity foundations are used in locations where depth is not available, such as on viaducts, or where ground conditions below the surface are poor.

11.11.6. Rock Foundations

Rock foundations are used where the railway runs through an area where bedrock is on or near the surface. The rock is usually dressed with a flat concrete bearing face, and holding down bolts are drilled into the rock and bonded with a suitable adhesive. Fractured rock strata can be especially problematic, and grouting or even rock-breaking may be necessary in these cases.

Figure 194: Rock anchor foundation. Sydney, Australia

11.11.7. Attachment to Other Infrastructure

Figure 195: OLE supported from station roofwork. Manchester, UK

In restricted clearance areas there is often not room for a dedicated OLE structure foundation. Typically, these areas are at:

- Stations;
- Overbridges;
- Underbridges;
- Cuttings with retaining walls.

In these areas it is necessary to attach OLE structures or assemblies to the existing infrastructure.

For these attachments, the OLE designer must take account of the following;

- Condition of the structure;
- Load capacity of the structure;
- Ownership of the structure (many bridge structures are owned by third parties, who may or may not consent to the fixing);
- Effect of fault current on structure and other systems and utilities attached to it;
- Electrical clearances;
- Fixing arrangements;
- Safety of the public.

It is often the case that other assets such as signal heads, CCTV or depot lighting can be attached to OLE structures. In this case it is necessary to consider management of earthing, and safe access for maintenance.

Figure 196: Portal mast pedestal on outside of viaduct. Manchester, UK

11.11.8. Foundation Basic Designs

The basic design range of each OLE system (section 17.9.2) generally contains a number of foundations, which are pre-approved for use at appropriate locations. Foundations are allocated (section 18.4.4) based on the constraints at the location, geotechnical conditions, embankment stability, any environmental constraints, and the construction methodology.

Where standard foundations cannot be allocated, specially designed foundations are used, and these are subject to a civil/structural approval procedure.

11.12. OLE Assemblies

A full description of the often-confusing and contradictory terminology used in OLE design and construction (in common with most engineering sectors) is beyond the scope of this book. The following diagrams give an overview of a few the terms used.

Below is a *pull-off* cantilever; so-called because the assembly staggers the wire toward the mast.

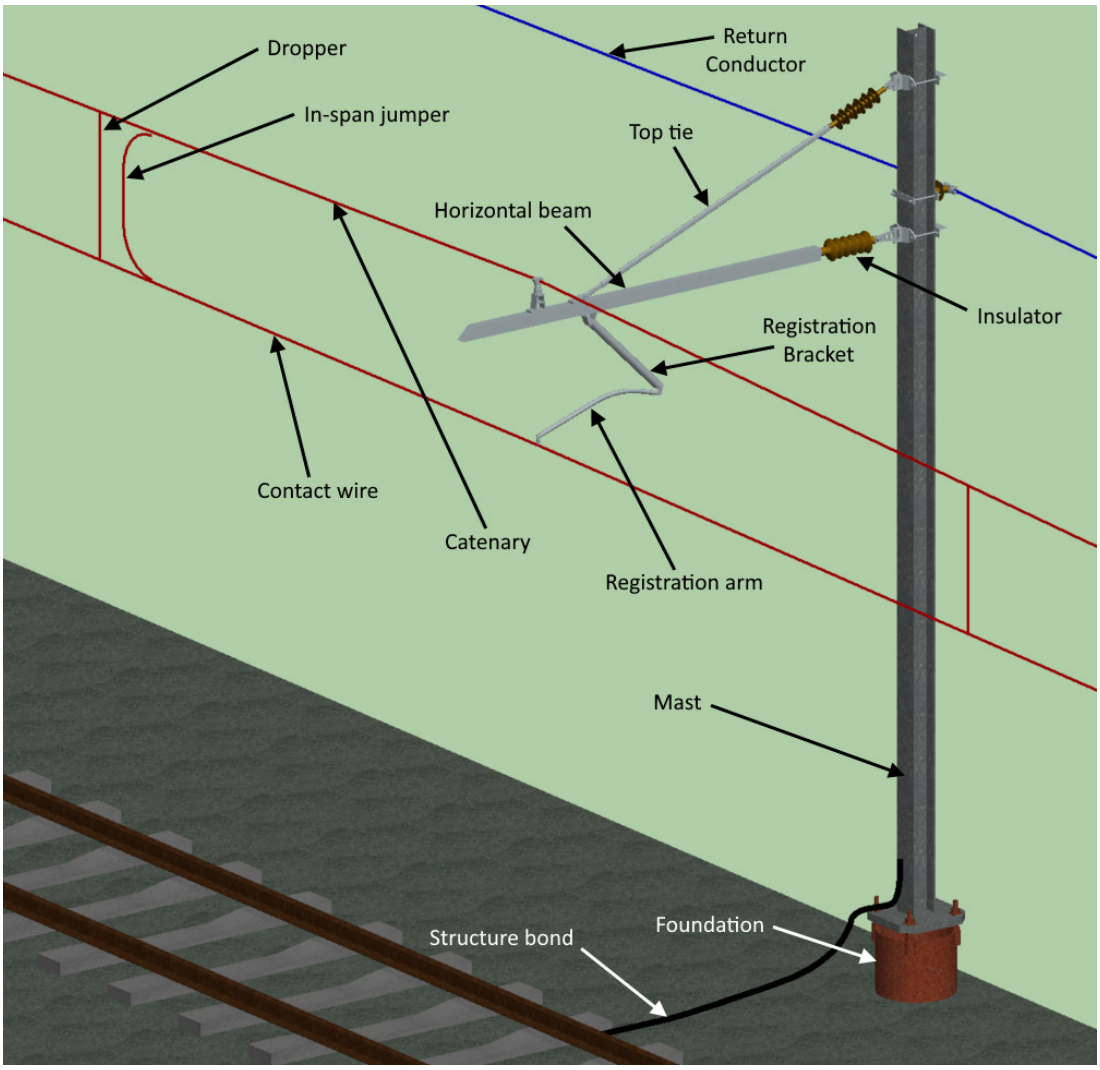


Figure 197: Typical modern pull-off cantilever, with classic feeding, return conductor and structure bonding

Overleaf is a *push-off* cantilever (sometimes known as a *push-pull* cantilever); so-called because the assembly staggers the wire away from the mast.

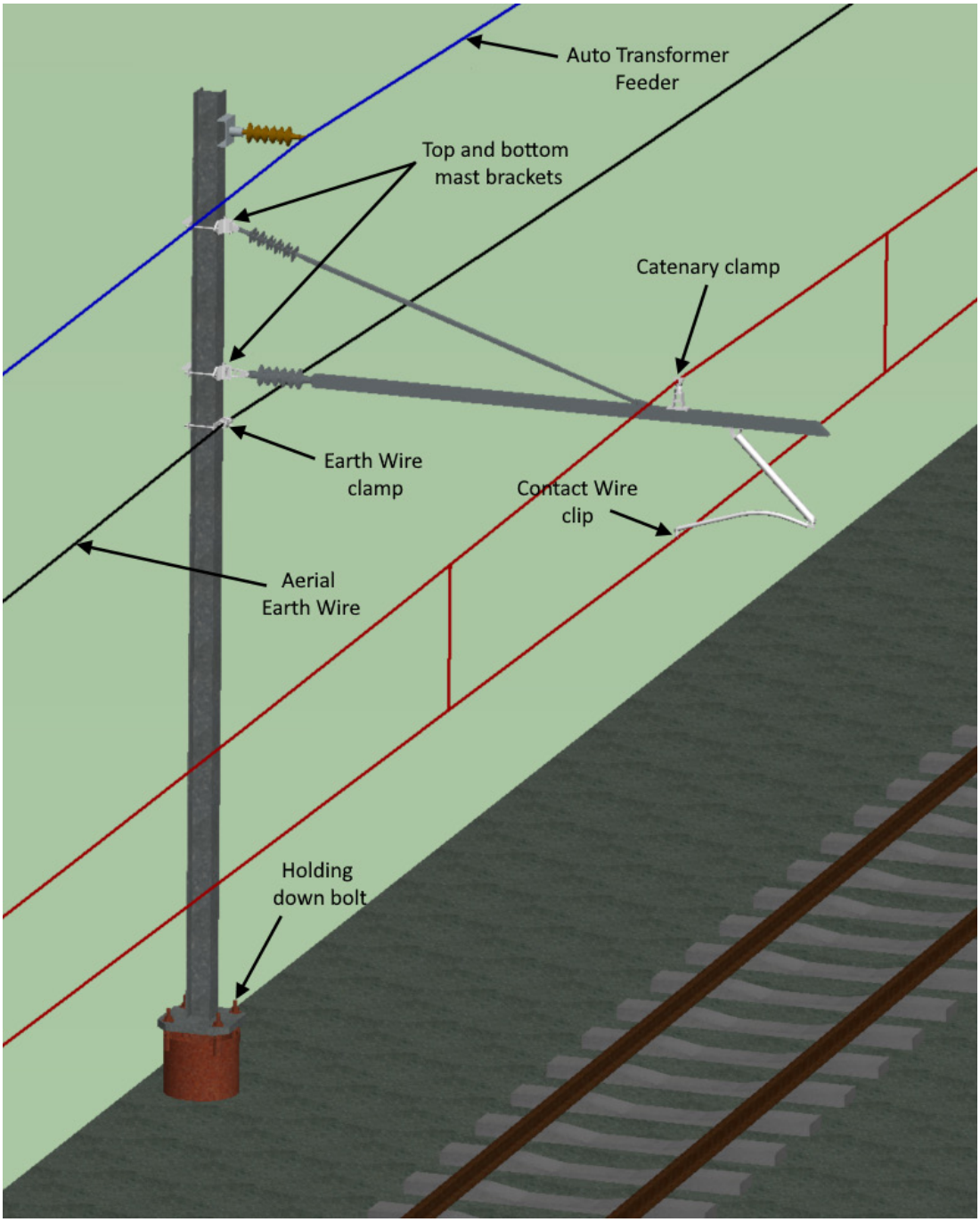


Figure 198: Typical modern push-off cantilever, with auto transformer feeding and aerial earth wire

11.13. OLE Geometry

The requirement for continuous contact between the OLE and the pantograph means that the geometry of the system must be kept within strict limits. It is important to ensure that the OLE geometry complies with the rules set out below. Failure to do so will compromise the reliability – and potentially safety – of the system.

The contact wire geometry is defined in terms of *height* and *stagger* at each structure. The height is measured parallel to the track centreline; the stagger as the offset perpendicular to it.

11.13.1. Vertical Geometry

The vertical range is limited by the pantograph operating range (section 11.1.2). Therefore each system has both a minimum and maximum *contact wire height*. Above the upper limit, the pantograph will auto-drop leading to loss of power; below the minimum height electrical clearances to the train will be compromised. The requirement for height variation arises from the need to achieve minimum safe clearance for road and pedestrian traffic at level crossings (section 16.11), and to operate through low overbridges.

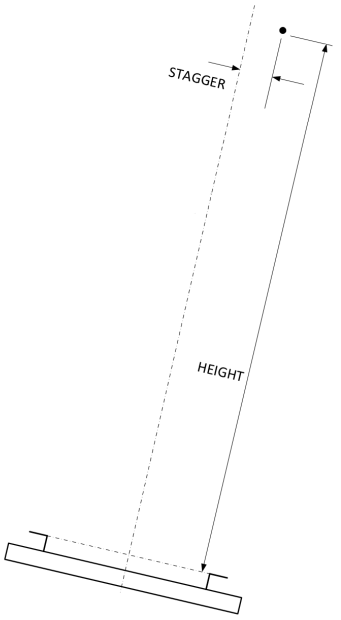


Figure 199: Height and stagger for OLE

Modern high speed lines, however, are usually new construction, with no level crossings (due to the unacceptable safety risks), and overbridges built to give generous clearances. In these circumstances it is possible to maintain a constant contact wire height throughout the route. For instance in the UK, High Speed One has a contact wire height variation of only 0.01m.

For systems where there is a need for height variation, the pantograph has a maximum rate of rise and fall per second, above which it will not be able to follow the wire. Therefore the rate of rise and fall of the wire over the pantograph – the *contact wire gradient* - must be controlled if good current collection is to be achieved. The maximum gradient is generally proportional to the maximum linespeed – for instance European Standards[143]specify maximum gradients ranging from 1 in 40 at 50km/h to 1 in 1000 at 250km/h. A useful rule of thumb for good current collection is:

$G_{max} \leq 1$ in $(5v)$

where v is measured in mph.

Additionally, areas of gradient change are subject to profile rules as below. Failure to control gradient, and change of gradient, can lead to long term current collection problems and locally increased contact wire wear.

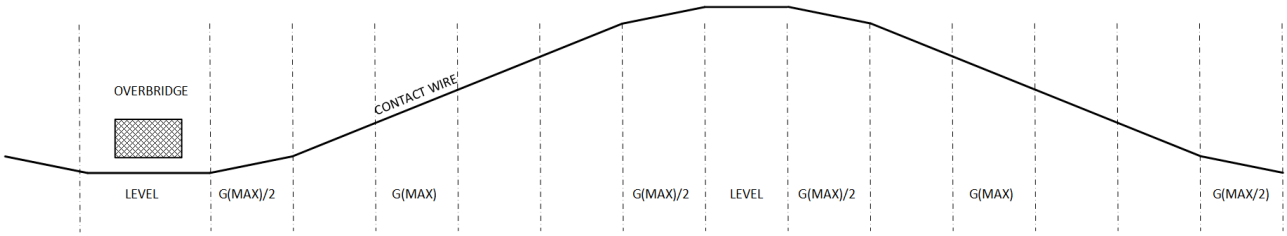


Figure 200: Typical contact wire profile (y axis exaggerated)

Note that gradients are always measured relative to track gradients rather than a fixed point in space. The maximum gradient generally can only be achieved by means of an intermediate span with a half maximum gradient. Gradients can be quoted either as "x%" (used in Europe) or as "1 in y" (in the UK).

[143] BS EN 50119:2020 "Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines"; April 2020; BSI; section 5.10.3.

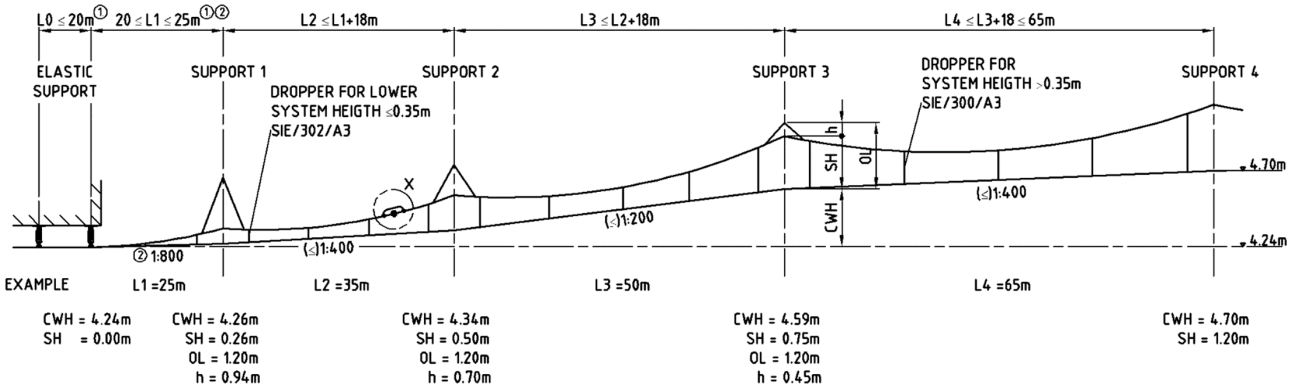


Figure 201: Typical twin contact bridge profile

At low overbridge locations, the *system height* (the distance between the contact wire and catenary) is reduced and contenary (section 10.8) used. For very low bridges the system height is eliminated by using a *twin contact* arrangement, where contenary is spliced into the catenary and then brought down until it is side by side with the contact wire.

The design of OLE through the overbridge itself must be carefully managed. It is essential to maintain sufficient clearance from all live parts – including the pantograph – to both the bridge structure above and to the side, and to the train below. This must include allowances for track maintenance, OLE maintenance, train sway, OLE uplift and the depth of the live equipment itself.

Although the diagram overleaf shows the vertical build-up of clearances under a bridge, this approach is too simplistic to be used on its own. It is essential that lateral clearances are also considered, and as a general rule, the more complex the bridge shape, the more the design has to be considered as a three-dimensional problem. At arched bridges, the pantograph is often the constraining clearance.

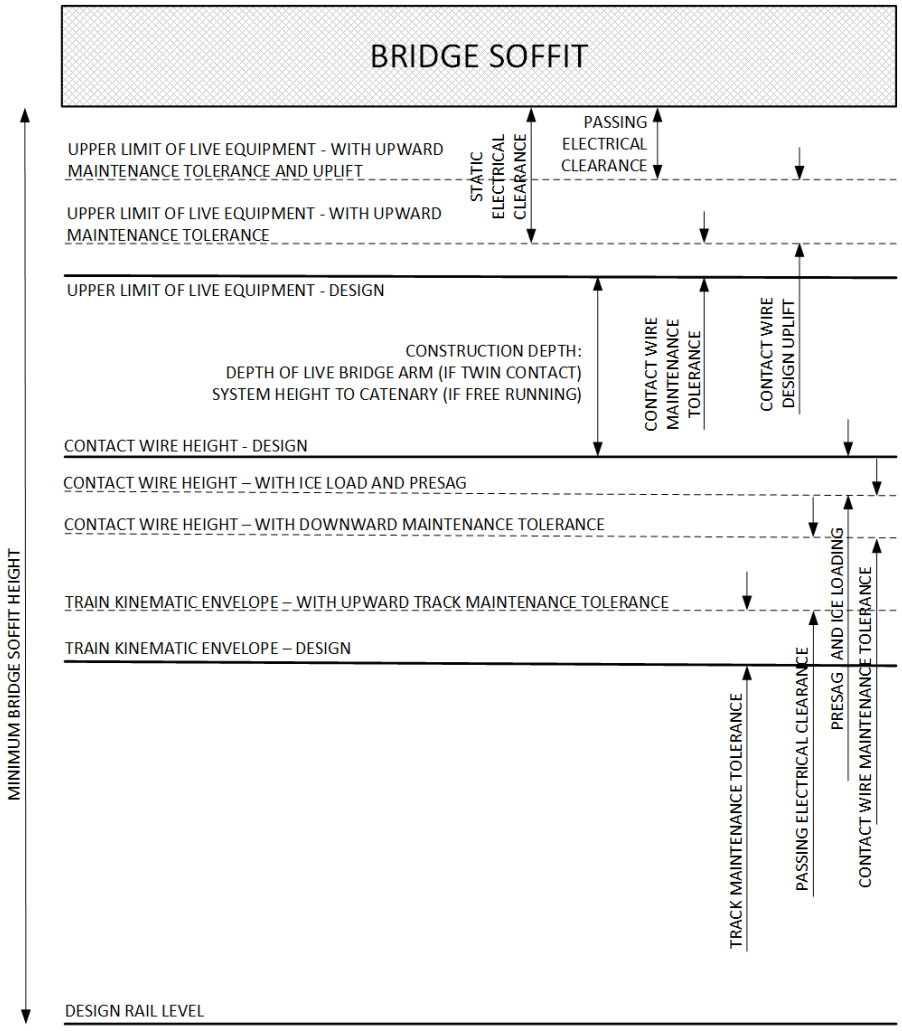

BRIDGE SOFFIT
UPPER LIMIT OF LIVE EQUIPMENT - WITH UPWARD MAINTENANCE TOLERANCE AND UPLIFT
STATIC ELECTRICAL CLEARANCE
PASSING ELECTRICAL CLEARANCE
UPPER LIMIT OF LIVE EQUIPMENT - WITH UPWARD MAINTENANCE TOLERANCE
UPPER LIMIT OF LIVE EQUIPMENT - DESIGN
CONSTRUCTION DEPTH:
DEPTH OF LIVE BRIDGE ARM (IF TWIN CONTACT)
SYSTEM HEIGHT TO CATENARY (IF FREE RUNNING)
CONTACT WIRE MAINTENANCE TOLERANCE
CONTACT WIRE DESIGN UPLIFT
CONTACT WIRE HEIGHT - DESIGN
CONTACT WIRE HEIGHT – WITH ICE LOAD AND PRESAG
CONTACT WIRE HEIGHT – WITH DOWNWARD MAINTENANCE TOLERANCE
TRAIN KINEMATIC ENVELOPE – WITH UPWARD TRACK MAINTENANCE TOLERANCE
TRAIN KINEMATIC ENVELOPE – DESIGN
TRACK MAINTENANCE TOLERANCE
PASSING ELECTRICAL CLEARANCE
PRESAG AND ICE LOADING
CONTACT WIRE MAINTENANCE TOLERANCE
MINIMUM BRIDGE SOFFIT HEIGHT
DESIGN RAIL LEVEL

Figure 202: Build-up of clearances at an electrified overbridge

If adequate clearances cannot be provided through an existing overbridge, then the air gap must be increased; either by jacking or reconstruction of the bridge, or by lowering the track. Neither of these options is straightforward or cheap.

The free uplift (section 11.1.2) is the uplift the system must be capable of catering for without failure. For bridge arrangements where clearances are restricted, support and registration assemblies which restrict the uplift are available (section 11.10.9).

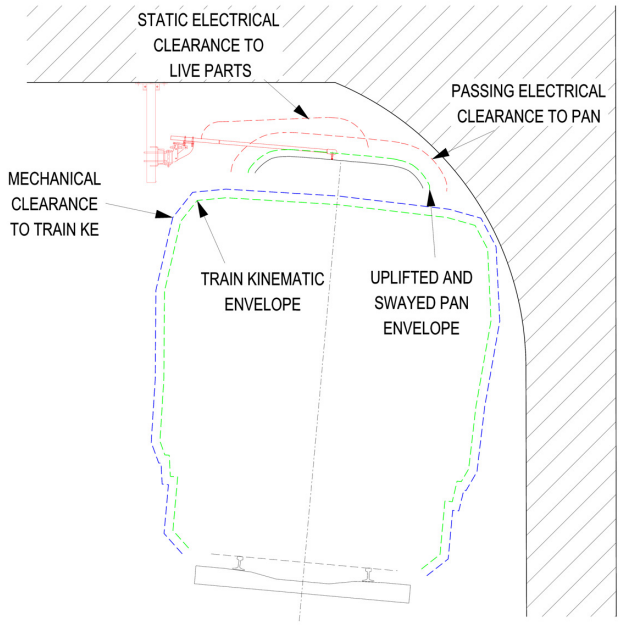

STATIC ELECTRICAL CLEARANCE TO LIVE PARTS
PASSING ELECTRICAL CLEARANCE TO PAN
MECHANICAL CLEARANCE TO TRAIN KE
TRAIN KINEMATIC ENVELOPE
UPLIFTED AND SWAYED PAN ENVELOPE

Figure 203: Mechanical and electrical clearances at a bridge

An additional consideration is the *span differential* for each OLE structure. This is the difference between the span lengths either side of the structure. A large span differential corresponds to a large elasticity differential between the two spans of OLE, and this can affect current collection. Objective evidence of this effect is hard to come by, but nevertheless most UK systems have a maximum permitted span differential.

Conversely, having a large number of equal spans can produce a mechanical resonance effect known as *galloping* where wind gusts and/or passage of trains at a specific speed can produce a standing wave in the wire which can lead to dewirement. For this reason many administrations have a limit on the number of equal spans, and require the introduction of a longer or shorter span to break up the resonance.

11.13.2. Horizontal Geometry

Figure 204: Contact wire staggering on tangent track. East Boldon, UK

The pantograph also has a horizontal operating range (section 11.1), and contact wire deviation outside this limit runs the risk of the pantograph coming off the wire. The pantograph will then rise without restraint, and as it interferes with the wire, dewirement is a certainty.

The horizontal displacement of the contact wire from the pantograph centre line at registration points (stagger) is required to ensure even pantograph carbon wear and carry overhead line around a curve.

This leads to the concept of *maximum stagger*. The maximum stagger is not usually a constant value; as contact wire height increases, the *sway* of the pantograph created by train roll increases. This reduces the effective operating range of the pantograph, and so the maximum stagger is linearly reduced to compensate.

The stagger is achieved by restraining the contact wire with a registration arm. This assembly is attached to the structure by means of a *drop bracket*. The registration arm length is matched to the stagger – a *minimum stagger* is set – so that the pantograph does not come into contact with the drop bracket when the registration arm is raised to the design uplift. In particular, some arms are designed to reach over the pantograph centre line; others are not.

Staggers on a multi-track railway are usually all set in the same direction - opposing staggers should be avoided where possible as this brings cantilevers (section 11.10.1) on adjacent tracks into close proximity, with attendant electrical hazards when one track is isolated for maintenance (section 10.12) and the other remains live.

An associated parameter is that of the *heel setting*. This is the vertical distance from the contact wire to the attachment of the registration arm to the drop bracket. This, combined with the minimum registration arm stagger, ensures the pantograph does not hit the registration assemblies.

There are a number of different types of registration arm for use in different situations. Most arms on mainline systems are of the curved type to allow for uplift. The amount of curve is a function of the design uplift (section 11.13.1) – higher speed systems require deeper curved arms.

On slow speed systems where uplifts are smaller, straight arms are often used. These are sometimes also used on mainline systems with a large angle of inclination, to increase electrical clearances or clear a pantograph on an adjacent track.

By contrast, an *overreach arm* is used to reach over the first contact wire to reach the second at overlaps or turnout control structures.

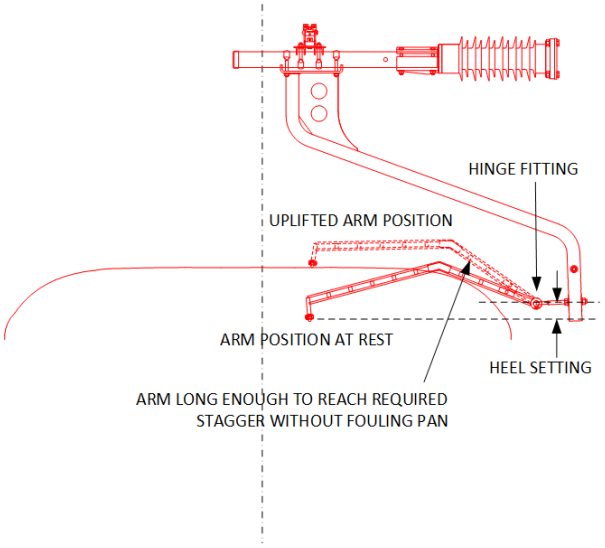


Figure 205: Minimum stagger and heel setting

Figure 206: (l-r) Mark 1 curved copper registration arm, HS1 overreach arms. Bushey and Stratford, UK

A knuckle is a registration assembly designed to provide staggering at a distance from an OLE structure, or where it is not possible to fit a conventional registration arrangement in.

Figure 207: UK1 knuckle. Rugby, UK

The point where the horizontal operating range is most at risk is at the *midspan* between the structures. This is because wind forces cause *blowoff* of the contact wire from its *still air* condition. This leads to the concept of *Maximum Total Offset* (MTO). This is the sum of *Midspan Offset* (MSO), blowoff, and *stagger effect*. The MTO for

each span must be less than the *Maximum Permissible Offset* (MPO). MPO is derived from the pantograph half width, sway and track tolerances, and includes a factor of safety to keep the contact wire away from the end of the operational width under all conditions[144].

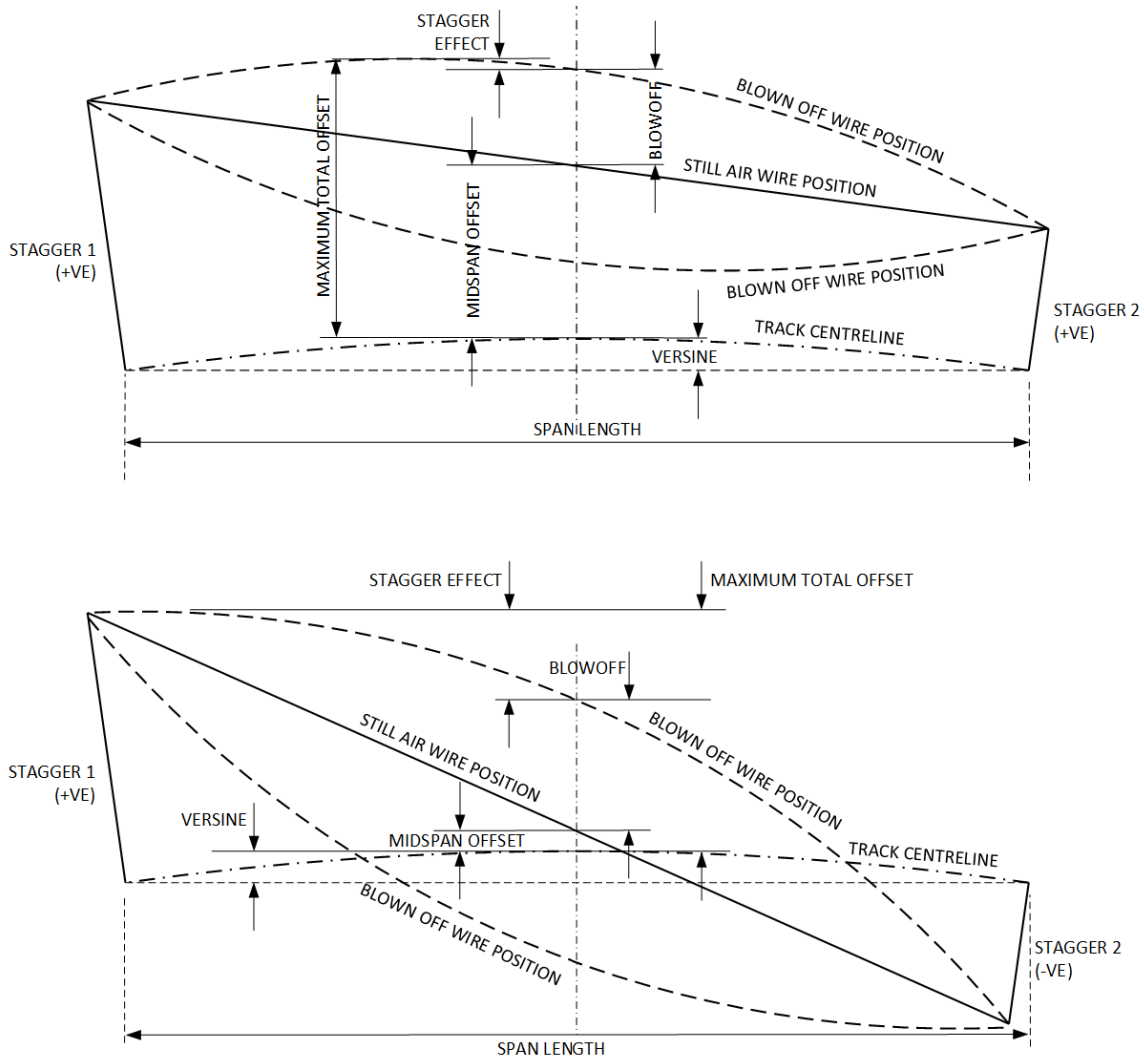


Figure 208: MSO, blowoff, stagger effect and MTO

MSO is the distance from the contact wire to the track centre-line under still air conditions midway between registration points. MSO is a function of the stagger at either end of the span, and the track curvature, measured as *versine* (also known as *stringline*). It is important to control MSO by varying structure spacing and stagger, since the other factors in the MTO are less easy to control. Smaller structure spacings are needed on small radius curves to keep MSO within limits.

Versine is measured using a straight line drawn from the running rail at one structure to the same rail at the next structure; the distance between this line and the same rail at the midpoint is the versine. Versine is a function of span length and track radius. If versine is too high then MSO will be compromised, and structures spacings must be reduced.

Blowoff is the amount through which the contact wire is moved at the midspan as a result of maximum wind conditions. It is a function of the contact wire tension, the contact wire *drag factor* (which is a measure of the

[144] "Overhead Line Equipment Design and Pantograph Interface", K. Warburton; 2015; IET.

aerodynamic drag of the wire), the contact wire surface area (diameter x length), and the *design windspeed*.

Stagger effect is the difference between the worst deviation in the span under wind, and the deviation at midspan – when the staggers at each end of the span are not the same in magnitude and direction, the MTO may not occur at midspan. The stagger effect figure is added to the midspan offset and blowoff to find the MTO.

Similarly to maximum stagger, MPO is not a constant, due to the increased sway of the pantograph with height. MPO is reduced linearly to compensate for this sway.

Sweep is the distance the contact wire moves across the pantograph in the course of travelling between two registration points, be it either from one side to the other, or from one side to the centre line and back again. *Sweep ratio* is the ratio of this distance to the span length; it is thus a measure of the speed of the contact wire movement over the pantograph.

It is important to keep the sweep ratio between minimum and maximum values across a whole OLE route, since if the contact wire moves too little, the carbons may wear unevenly. This can cause the pantograph to 'snatch' as the contact wire passes over the carbon discontinuity. Sweep ratio is less important on individual spans.

11.14. Assembly Loadings

The OLE support and registration is subject to a number of mechanical loads. These are;

- *Permanent vertical loads*; the dead loads caused by self-weight of the equipment;
- *Ice vertical loads*; live loads created by the weight of ice on the wire under cold weather conditions;
- *Permanent radial loads*; dead loads caused by a component of the wire tension being transferred to a structure when the wire changes direction due to stagger;
- *Wind radial loads;* live radial loads created by the action of wind on the wire.

The support and registration components must be capable of withstanding all of these loads in combination. In particular, the permanent and wind loads affect the operation of the support and registration assemblies, since registration arms (section 11.13.2) behave poorly if not held in tension. If there is little or no tension, the registration arm will "chatter" at the drop bracket fitting, and electrical arcing may occur across the fitting, eventually causing failure through erosion. At the other extreme, too much radial load can lead to failure of the registration arm fittings.

If there is a compression load on the registration arm, the combination of self-weight load and radial load results in a downward force, creating a hard spot. In extreme cases the registration arm could flip around, with catastrophic results for the next train. Most systems have special registration arms designed specifically to take a compression load, since there are occasions where there is no other practical option.

Figure 209: Series 1 compression arm with uplift stop (arrowed); note compressive radial load from wires. Newbury, UK

For all these reasons it is important to keep the registration arm load within design limits, by adjusting stagger and versine. The effect of versine on radial load is approximately four times that of stagger, so structure spacing on curves is key.

The same limitations apply to a lesser extent on the catenary support; there is a maximum vertical and radial load. Most support arrangements are capable of taking compression loads; however care should be taken with cantilever arrangements which use a top tie wire rather than a top tube, as these can collapse if sufficient compressive radial load is applied.

A partial factor (section 11.9) is applied to all maximum loads. This factor of safety is generally lower for registration assemblies than for structures; for instance, UK heavy rail typically uses a factor of safety for assemblies of 1.3 to 1.4.

11.15. OLE Materials

The choice of materials for OLE fittings is critical – the components being subjected to a variety of electrical and mechanical stresses as well as environmental conditions, with very limited inspection and maintenance access.

Most fittings in modern OLE are galvanised malleable cast iron, aluminium or (increasingly) stainless steel and copper alloy. Historically, galvanised mild steel was more common. Moving connections are typically either ball and socket, or hook and eye, to provide the required degree of freedom.

Figure 210: Modern cantilever showing a mix of galvanised steel, stainless steel, aluminium and cast CuNiSi fittings. Stratford, UK

The advantages and disadvantages of various materials are outlined below.

Material	Advantages	Disadvantages
Copper	Excellent electrical conductivity; resilience to fault current; excellent corrosion resistance	Expensive; theft risk; less commonly available; relatively heavy for a given strength
Copper alloys (CuNi, CuSn, CuZn)	Stronger than copper; better durability	Lower conductivity than copper
Galvanised steel	Low cost; easy to manufacture; low theft risk; commonly available	Lower conductivity than copper, copper alloys or aluminium; corrosion issues if galvanising is damaged; medium/high weight for given strength
Galvanised malleable cast iron	Easy manufacturing for cast items such as clips and clamps; well understood material; complex shapes can be made	Not suitable for long items; relatively heavy; galvanising prone to damage during short circuits
Stainless steel	Excellent corrosion resistance; acceptable weight for a given strength; good resilience to fault current/temperature	Higher coefficient of thermal expansion than galvanised steel; more complex to manufacture; lower conductivity than copper; can cause electrolytic corrosion when in contact with less noble metals
Aluminium	Generally lighter weight for a given strength; low price/weight ratio; good conductivity; good atmospheric corrosion resistance in neutral pH atmospheres	More specialist manufacturing, cutting and welding needed; issues around bimetallic corrosion need careful management; prone to damage if handled or stored without care
Aluminium alloys	Stronger than aluminium	Lower conductivity than aluminium
Tinned copper	All the benefits of copper, plus: prevents bi-metallic interfaces with aluminium	Expensive; can corrode if coating is damaged
Phosphor bronze	Ideal plain bearing material for used where lubrication is marginal or non-existent; high wear resistance; excellent corrosion resistance; low friction; high fatigue resistance for a non-ferrous metal	Expensive; hard to form when hot; hard to machine; moderate conductivity

Fabricated or forged components are now favoured over castings, having the following advantages:

- Consistent quality is hard to achieve or detect with casting processes;
- Forged components are generally stronger than equivalent castings due to the smooth metal grain flow and elimination of voids;
- Forgings tend to have better dimensional accuracy than castings and so don't always require machining.

Forging is however relatively expensive due to the need for machined forging dies, and so is more economical for large quantities. Casting is cheaper than forging, and remains the only choice for complex shapes that are impossible to forge.

The type and quality of welding for OLE components requires careful consideration and quality assurance, since these interfaces are often carrying the heaviest loads.

Catenary wire is usually a copper alloy, but historically cadmium copper[145] and mixed steel/aluminium conductors were used. Other conductors are aluminium, copper alloy, or stainless steel. Non-ferrous materials are used for certain live fittings in contact with copper conductors.

11.16. Wire Types

The various wires used in the system are also chosen for their electrical and mechanical characteristics.

11.16.1. Contact Wire

The contact wire has five main requirements:

- To transmit electrical energy along its length;
- To transfer electrical energy to the pantograph (section 11.1);
- To withstand the mechanical stresses placed on it by the tension, environment and passage of trains;
- To withstand wear from the passage of trains;
- To facilitate connection for droppers (section 11.16.4), registration arms (section 11.13.2) and electrical connections.

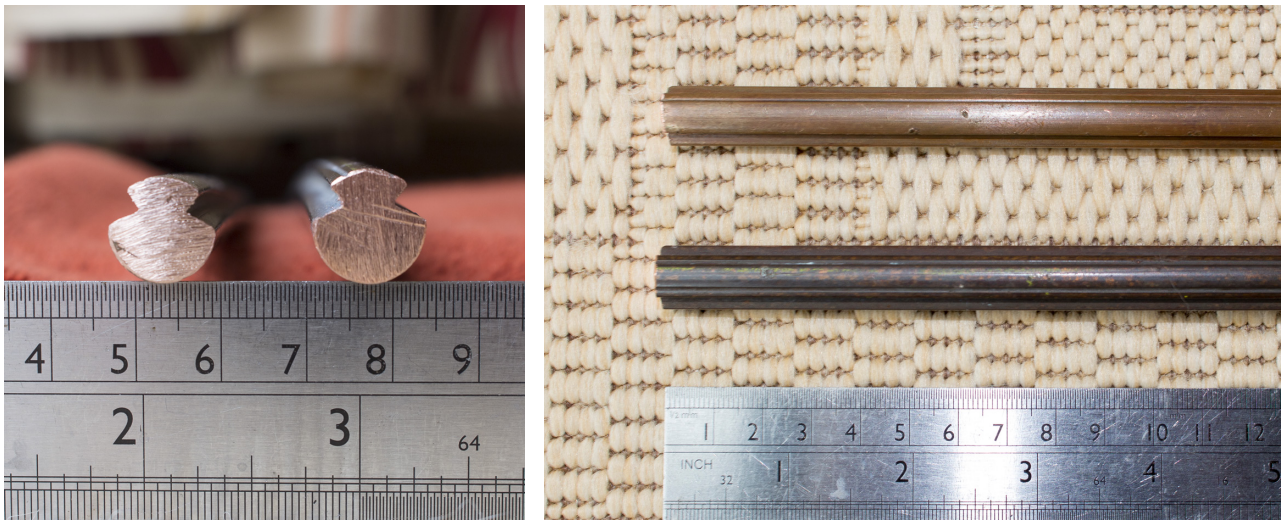


Figure 211: (l-r) 107mm^2 CuSn and 120mm^2 CuAg contact wire; note single and double identification grooves

Contact wire cross sections conform to a worldwide standard shape, which is a circular section with two notches for connection and support purposes. EU standards[146] are centred on 107, 120 and 150mm^2 sections. Larger sections have a larger wear allowance, but there is a trade-off with the higher weight. Some administrations use

[145] Cadmium copper is now prohibited in UK installation due to cadmium's status as a carcinogen and toxin.

[146] BS EN50149:2012 Incorporating corrigenda October 2015 "Railway Applications – Fixed Installations – Electric Traction – Copper and Copper Alloy Grooved Contact Wires"; 31 October 2015; BSI; section 4.5.4.

an oblate section rather than a circular one, to mitigate excessive wear on the pantograph in the initial period after construction, until a flat has worn on the wire.

Figure 212: Typical CuNiSi forged contact wire swivel clip. Iver, UK

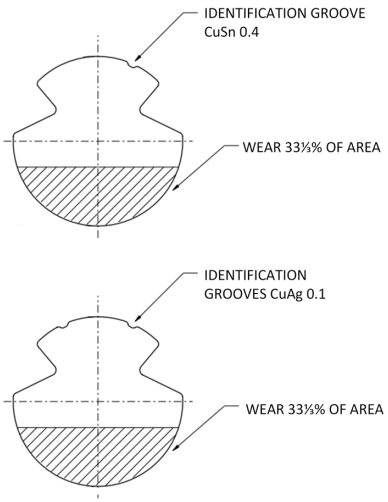


Figure 213: Typical CuSn and CuAg contact wire cross sections[147]

Contact wire material selection is generally a balancing of the mechanical and electrical requirements. The cross section must be kept as small as possible (to keep weight down) while keeping the conductivity high; however materials with a higher conductivity usually have a lower tensile strength and exhibit long-term stretching under tension, a behaviour known as *creep*.

Copper and copper alloy comprise the de-facto standard for contact wires, due to copper's excellent conductivity, tensile strength and hardness, as well as good performance under temperature change and corrosion resistance. Copper has the advantage of forming a hard but conductive oxidising layer when exposed to air.

Alloy additives are added to copper to improve the mechanical performance; however they reduce the conductivity to a greater or lesser extent. Therefore the material is chosen to balance these criteria for the particular system. For instance, hard drawn copper can be used up to a wire temperature of 80°C, beyond which the wire will begin to anneal and lose strength.

If higher operating temperatures are required, silver copper (CuAg) anneals at around 150°C and has otherwise identical electrical and mechanical properties[148].

European contact wires use a system of grooves along the top of the wire to identify the material type[149].

[147] 1/014/401/A3 "MkIIID A.T. Equipment - Conductor Particulars - Simple Catenary"; P04, 23 August 2008; Network Rail.

[148] "Overhead Line Equipment Design and Pantograph Interface", K. Warburton; 2015; IET; section 2.

[149] BS EN50149:2012 Incorporating corrigenda October 2015 "Railway Applications – Fixed Installations – Electric Traction – Copper and Copper Alloy Grooved Contact Wires"; 31 October 2015; BSI; section 4.4.

Number of Grooves	Type
0	Normal and High Strength copper
1 centred	Copper-cadmium alloy
1 offset	Copper-tin alloy
2	Copper-silver alloy

One of the key aims of the system design (section 17.9.1) is to deliver uniform low wear of the contact wire, since the life of a whole tension length (section 11.4) will be reduced should any sections experience excessive wear.

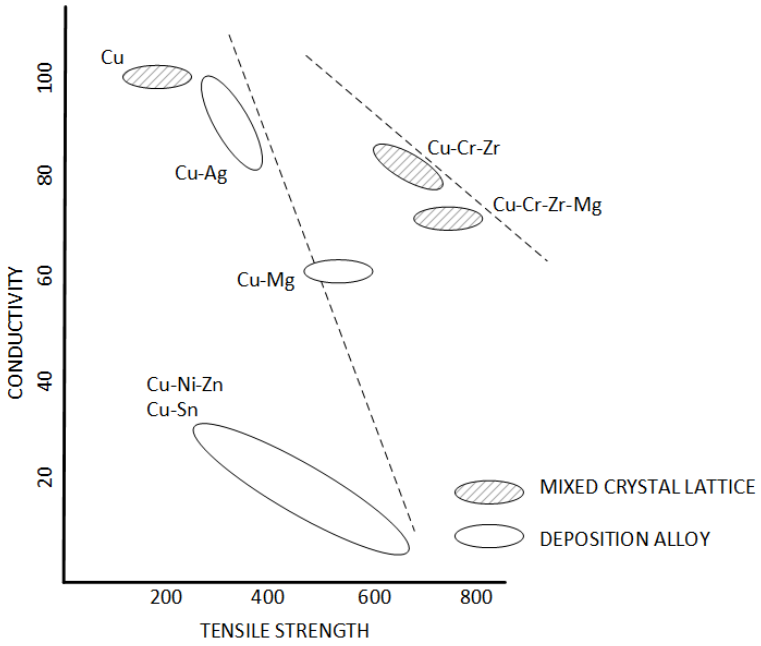


Figure 214: Contact wire strength against conductivity[150]

11.16.2. Rigid Overhead Contact Line

It is sometimes not practical, for a variety of reasons, to provide conventional OLE using flexible wires. In these cases a *Rigid Overhead Contact Line* (ROCL)[151] is used. This takes the form of a grooved bar designed to accept a conventional contact wire.

This system is only used in situations where conventional OLE is not feasible, since the bar requires frequent support, and so is more expensive than conventional OLE. However it has a number of advantages, including the lack of tension in the system and the ease of contact wire renewal compared with conventional systems. ROCL has now been certified as safe and reliable at speeds up to 275kph.

[150] "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p128.

[151] Also known by the trademarked name *Rigid Overhead Conductor System* (ROCS) or *rigid overhead conductor bar*. ROCL is used here in accordance with the definition in European Standards. BS EN 50119:2020 "Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines"; 30 April 2020; BSI; section 3.1.1.6.

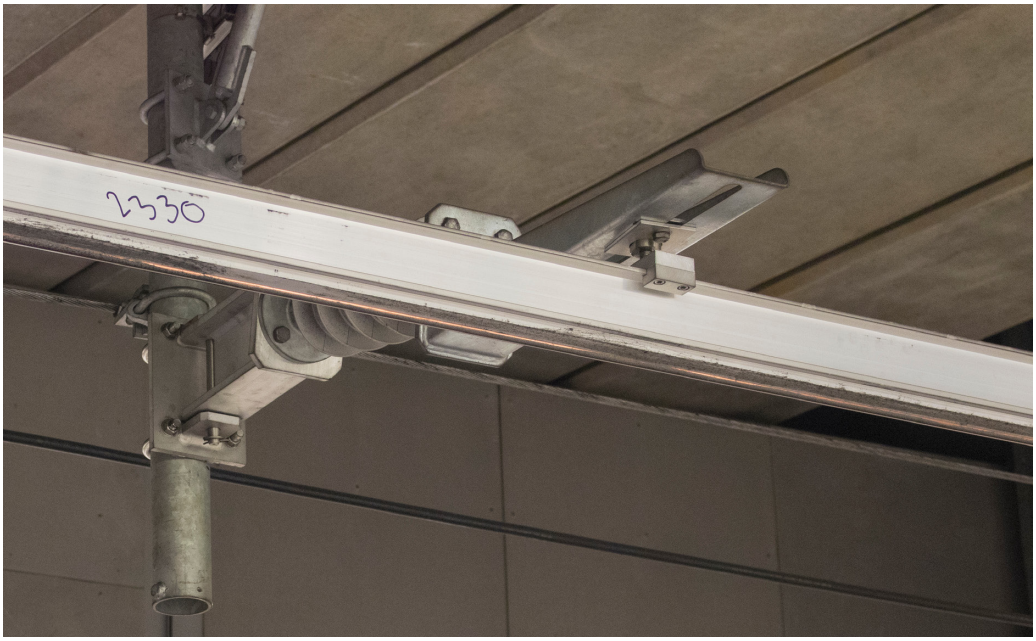


Figure 215: Balfour Beatty ROCL support. St Pancras, UK

Typical uses include:

- Tunnels where clearances are too small for conventional OLE supports and conventional levels of uplift (section 16.5.6);
- Tunnels and stations where fire and public safety requirements are such that a vulnerable tensioned system is not acceptable;
- Locations where OLE design is driven by aesthetic and architectural considerations. The risk of dewirement is so low with this system that an OCLZ (section 10.10.1) is not required;
- Locations where retractable or moving OLE (section 15.5) is required.

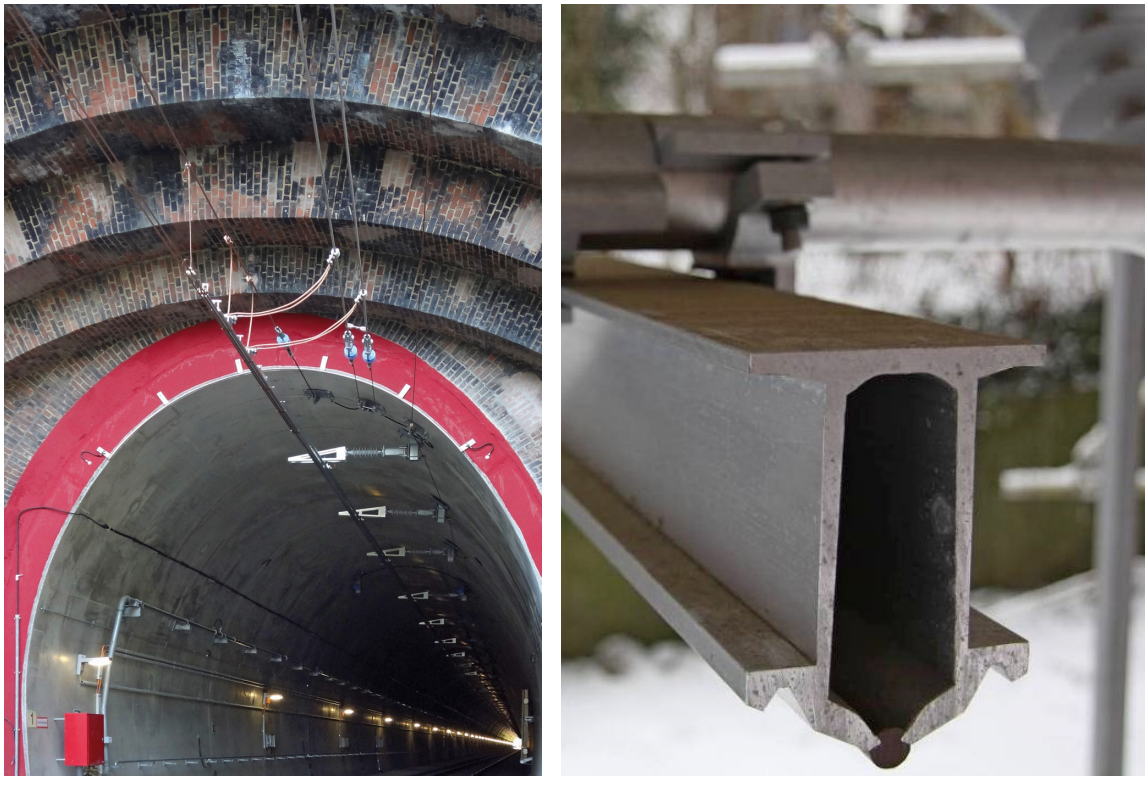


Figure 216: (l-r) Furrer+Frey overhead conductor bar transition, and close-up of bar. Buschtunnel, Germany and Bern, Switzerland

The transition from conventional OLE to ROCL must be carefully managed since the elasticity of the conductor bar is much lower. This is usually done with a transition bar section which has graduated cut-outs to provide increasing stiffness.

Figure 217: Rigid overhead conductor line as architecture. Salzburg, Austria

11.16.3. Catenary Wire and Auxiliary Catenary

The *catenary wire*[153] – and auxiliary catenary (section 11.2), if there is one – has fewer requirements than the contact wire; it is required to transmit electrical energy along its length and to withstand the mechanical stresses placed on it, but not to withstand pantograph wear or transmit energy across a small interface area.

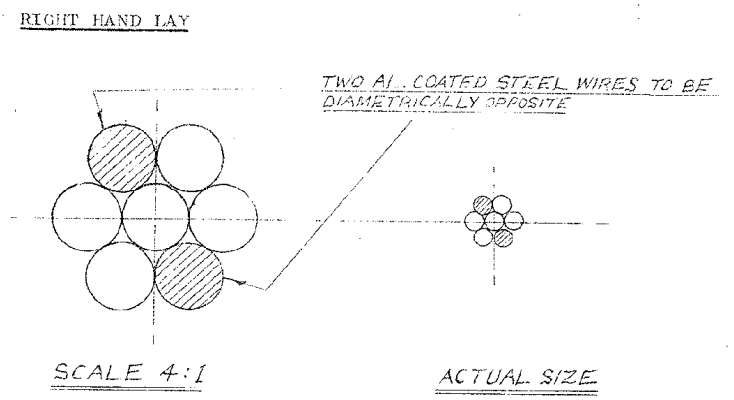


Figure 218: AWAC Catenary[152]

For this reason stranded wires are used for catenary wire. Pre- and post-war systems used hard drawn copper, but in the 1970s aluminium/steel *Alumo-Weld Aluminium Composite* (AWAC) catenary was widely used in the UK for reasons of economy. However this wire has given reliability issues, as the two steel wires – which give the conductor most of its strength – are prone to galvanic corrosion and failure if the aluminium coating is damaged by mishandling or flashover[154].

[152] OLEMI Drawing 1/148/075/A3 "Aluminium Covered Steel-Aluminium Conductors"; rev 3; BICC; 1979.

[153] This conductor is known as a messenger wire in Europe and the US.

[154] NR/L2/ELP/27009/MOD C64 "Overhead Line Campaign Changes – Renew AWAC Catenary prone to failure due to Corrosion of the Stainless Steel Inner Cores"; Issue 1, 2011; Network Rail.

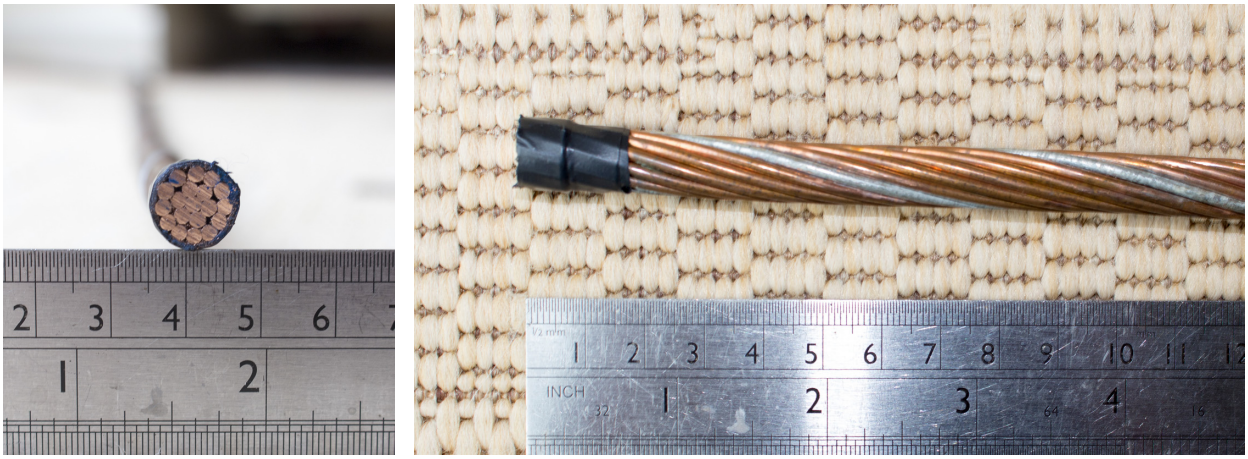


Figure 219: 19/2.1 Bz II catenary; note two tinned strands identifying wire as bronze

Current best practise for catenary is to use copper alloys such as Bz II.

11.16.4. Droppers

All *droppers* have two main requirements:

- To hold the contact wire at the correct height relative to the catenary;
- To withstand the unloading/loading cycle created by the passage of trains.

Traditionally droppers have not had an electrical function, but modern systems increasingly use *current carrying droppers* with suitable electrical connections to improve resilience to potential differences between catenary and contact wire.

For locations with small system heights, a conventional dropper would be subject to excessive flexing due to pantograph passages, and so an *uplift dropper*, without a fixed catenary connection, is used instead.

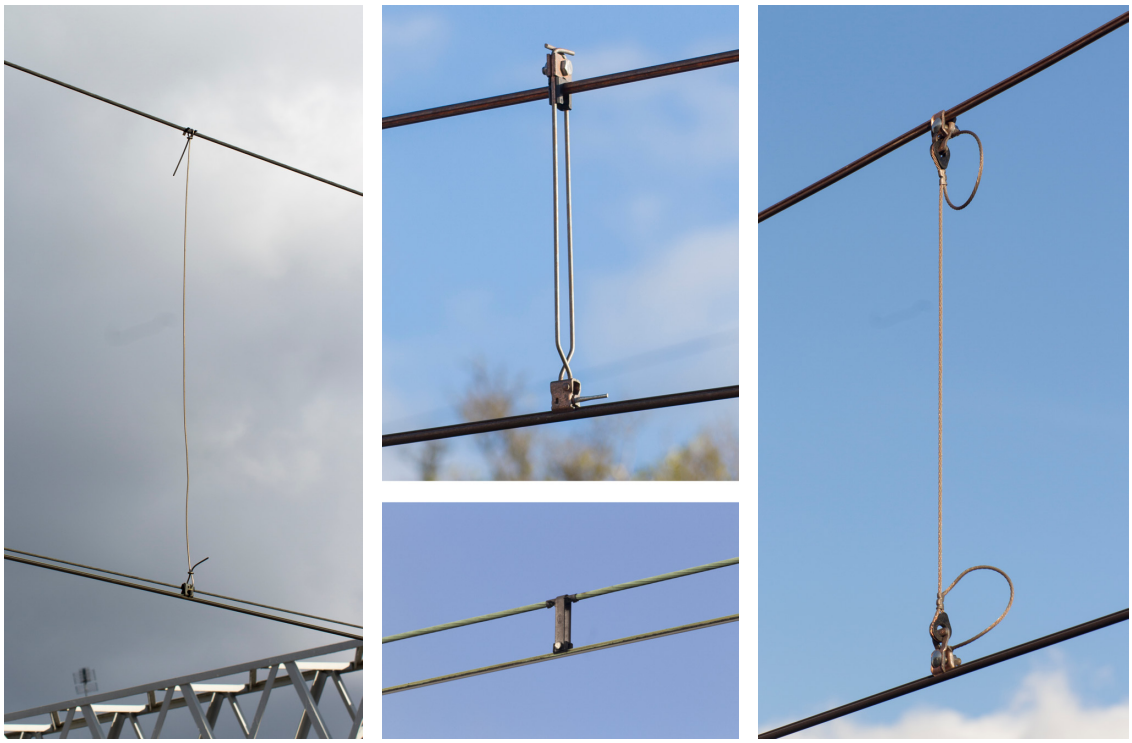


Figure 220: (clockwise from left) Dropper types; non-current carrying, chopsticks uplift, current carrying, loop uplift

Figure 221: (l-r) Arthur Flury Bz II flexible current carrying dropper with CuNiSi clamps, catenary attachment and contact wire attachment

Droppers (other than uplift types) have historically been made from solid copper wire or galvanised steel wire; however these are prone to long-term failure due to the cyclic loading / unloading created by the passage of trains. Modern droppers use a stranded copper alloy wire, which is more expensive but gives better load cycle performance.

11.16.5. Ancillary Conductors

Conductors which are not contact wire or catenary, but carry traction and/or fault current, are collectively known as *ancillary conductors*.

Return Conductors (section 10.4.1) have historically used 19/3.25 mild steel or 19/3.25 hard drawn copper, but modern systems in the UK use aluminium as a good balance of conductivity and corrosion resistance versus cost. Current standard wires are 19/3.25 Al (given the codename *hornet* in British standards[155]) or 19/4.22 Al (*cockroach*), depending on electrical load. These are used as bare cables in open route, and with a PVC sheath in accessible areas such as stations.

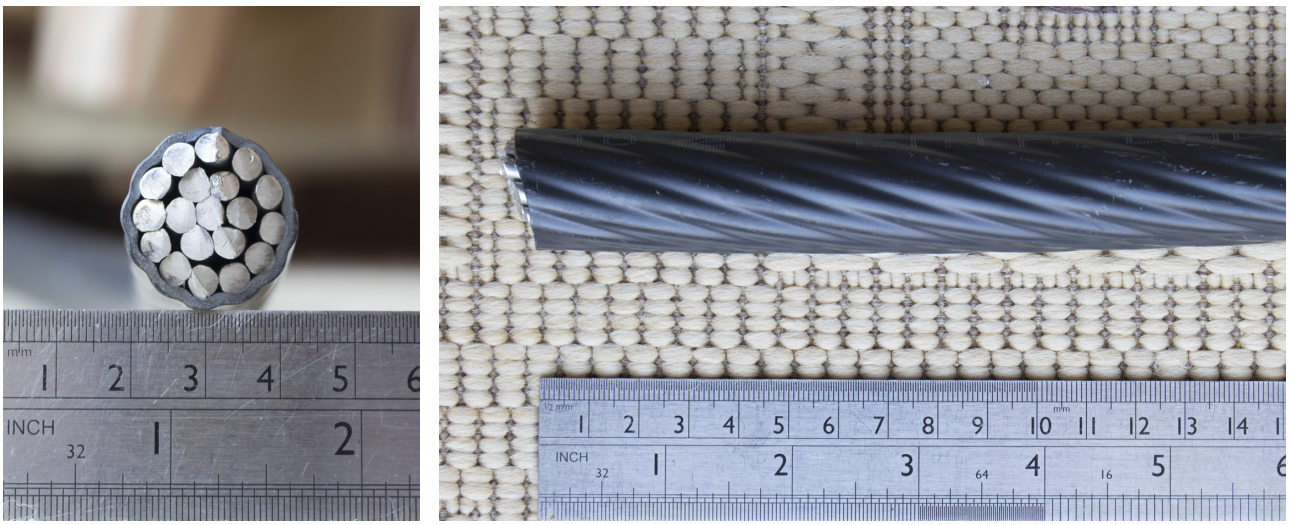


Figure 222: 19/3.25 PVC sheathed Al cable, used in the UK as bonding cable; minus the PVC sheath it is also used as earth wire and return conductor

[155] BS215-1:1970 "Aluminium Conductors and Aluminium Conductors, Steel-Reinforced – For Overhead Power Transmission – Part 1: Aluminium Stranded Conductors", March 1970; BSI; appendix C.

19/3.25 Al is also used for aerial earth wire, although some systems use the *All Aluminium Alloy Conductor* (AAAC) equivalent 19/3.35 to eliminate creep. 19/4.22 Al (with a PVC sheath) is also used for MSCs and RSCs (section 10.4.5), which being ground-mounted and untensioned do not suffer from creep.

Cross track feeder wires (section 11.7.2) typically use the same aluminium conductors as return conductors, although more recently 37/2.27 hard drawn copper has been used when connecting to copper catenaries, so avoiding the need for bimetallic lugs (section 11.17.2) and associated complex wire connections, which are a known failure mode.

ATF conductors (section 10.4.3) typically use one or two 19/4.22 Al wires (depending on electrical load), but for heavily loaded areas a 37/3.78 Al wire (*centipede*) is used. Since ATFs are live they need greater sag control than EWs or RCs to prevent them coming too close to the ground. This means higher tension which exacerbates creep, and so recently a 19/4.2 AlMgSi AAAC wire has been used.

Tail wires (section 11.4.5) must withstand the combined tension of the contact wire and catenary and so are a proportionally larger section. Standard UK practise is to use 37/2.36 hard drawn copper wire.

Jumpers (section 11.4) typically use 40mm^2 to 70mm^2 flexible stranded hard drawn copper wire, depending on electrical load.

Bonding cables (section 10.10.1) typically use 19/3.25 or 19/4.22 PVC sheathed Al cable depending on electrical load.

11.16.6. Other Wires

Headspan structures (section 11.10.7) comprise three horizontal wires; from top to bottom, these are the headspan wire, the upper cross span wire and the lower cross span wire. These are not current-carrying in normal operation and so are arguably not conductors. The upper and lower span wires are nominally taut and in the UK these use 19/2.1 hard drawn copper, although historically 19/1.85 copper covered steel wire (known as *copper ply*) was used for reasons of economy. The copper ply is prone to damage if rough handling is experienced during construction. This led to instances of water ingress and subsequent corrosion, and so as with AWAC (section 11.16.3) a programme is under way to replace them with Bz II[156].

Figure 223: Headspan span wire clamp and RC support

The headspan wire provides the mechanical support for the whole configuration, and for this function a 19/1.63 stainless steel wire is the norm in the UK. For large headspans these are doubled up to provide sufficient

[156] NR/L2/ELP/27009/MOD C17 "Overhead Line Campaign Changes – Replace Copper Ply Span and Tail Wire"; Issue 1, 2011; Network Rail.

mechanical strength. The vertical headspan droppers which support the OLE registrations typically use solid 8mm galvanised steel wire.

MPA tie wires (section 11.10.11) generally use the same wire as the catenary wire for the system. MPA tie wires are usually tensioned at between 3 and 5kN at the setup temperature for the system.

All of the wires discussed so far are designed to be broadly static, and subject to movement only from wind and passing trains (with the exception of tail wires). Some wires need to withstand frequent and significant flexing without fatigue – for instance the connection between a fixed post insulator and a moving blade insulator (section 11.7) of an isolator. For these connections a *flexible braid* is used.

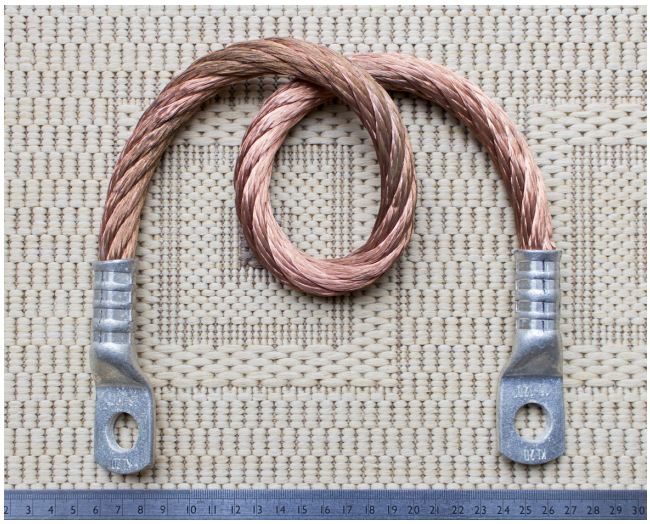


Figure 224: Flexible copper braid connection

These comprise a very large number of small diameter strands – usually copper – which are woven into ropes which are capable of carrying high currents, but remain extremely flexible.

11.17. Wire Connections

A variety of connections are required in and onto OLE conductors, and these can be divided into two groups – tensioned and untensioned. All such connectors are part of the electrical system, and must be able to withstand repeated thermal cycles and fault currents without degradation of the connection.

11.17.1. Tensioned Connectors

These connectors are placed directly into the conductor, either as part of the termination onto a mast or boom, to effect the transition from one wire to another, or to create an electrical break with a cut-in insulator (section 11.18). As such they experience the same tension as the wire and are safety-critical, since failure will inevitably result in a dewirement.

For many years the standard means of terminating a stranded wire was a *dead end clamp*, a cast iron fitting comprising an outer sleeve which carries a clevis, and an inner wedge. For stranded wires, the wire is bent around the wedge, and the tension in the wire pulls the wedge into the dead end sleeve and secures the wire.

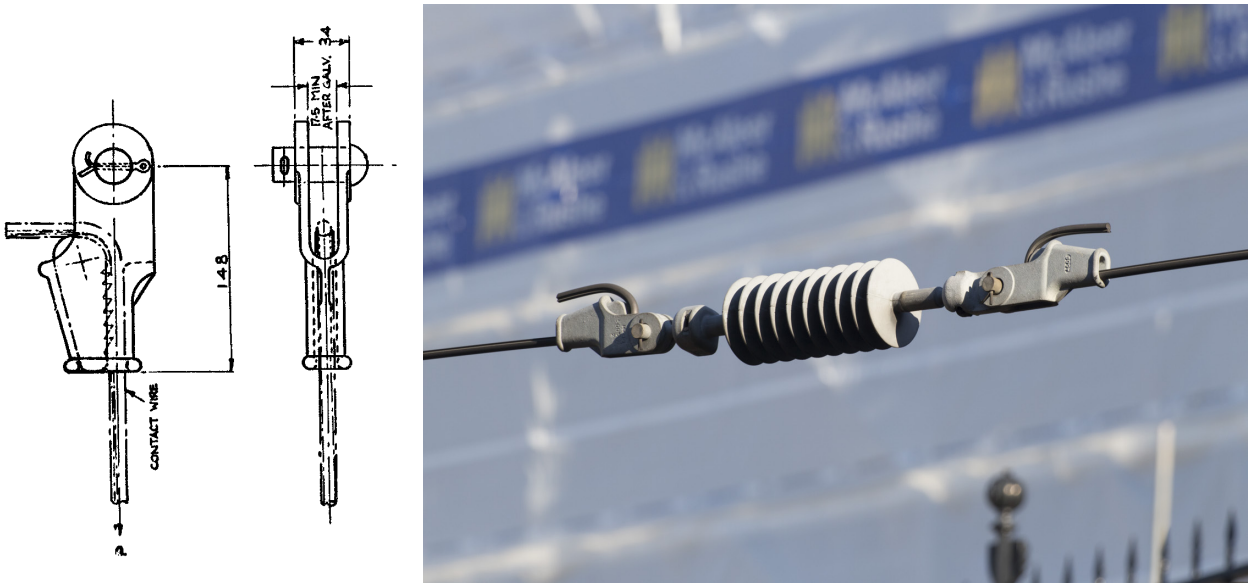


Figure 225: Dead end clamp fittings for contact wire cut-in insulator

For solid conductors such as contact wire, a variation on this design was used with the conductor bent through 90° rather than back on itself.

An alternative for terminating stranded wires was later adopted from the electricity supply industry – the *preformed dead-end* (also known as a *PLP* after the manufacturer). This uses a prefabricated set of three copper or aluminium covered steel wire strands (to match the conductor) which are spiral wound, formed into a U-shape and bonded together with a liberal coating of resin and grit. This is then threaded around a terminating casting and the strands spiral wound around the wire in the same direction as the wire layup. The action of the wire tension pulling on the PLP tightens it around the wire, and the friction of the resin coating ensures that the wire does not slip.

Figure 226: Preformed dead end grip termination for AWAC termination

Preformed dead ends require a high level of care in installation[157], and this led to the use of the *cone end fitting*; which uses a conical hollow brass wedge which sits around the central strands of the wire, with the outer strands arranged outside it. The wire tension pulls the conical wedge into a conical gunmetal sleeve which carries the clevis, and the outer strands provide the necessary friction to hold everything in place.

Figure 227: Cone end clamp for catenary termination

Most of these traditional termination devices have now been replaced by the *forked collar socket*. These are a modern form of cone end fitting, but the whole of the wire sits inside a forked collar, which has grooves or *collets* machine into it. These allow the collar's diameter to reduce as the outer sleeve compresses the collar under tension. The design removes the need for skilled setup and are less prone to failure, but they require a reliable minimum tension to operate correctly, and so low tension wires such as spanwires still use dead end clamps.

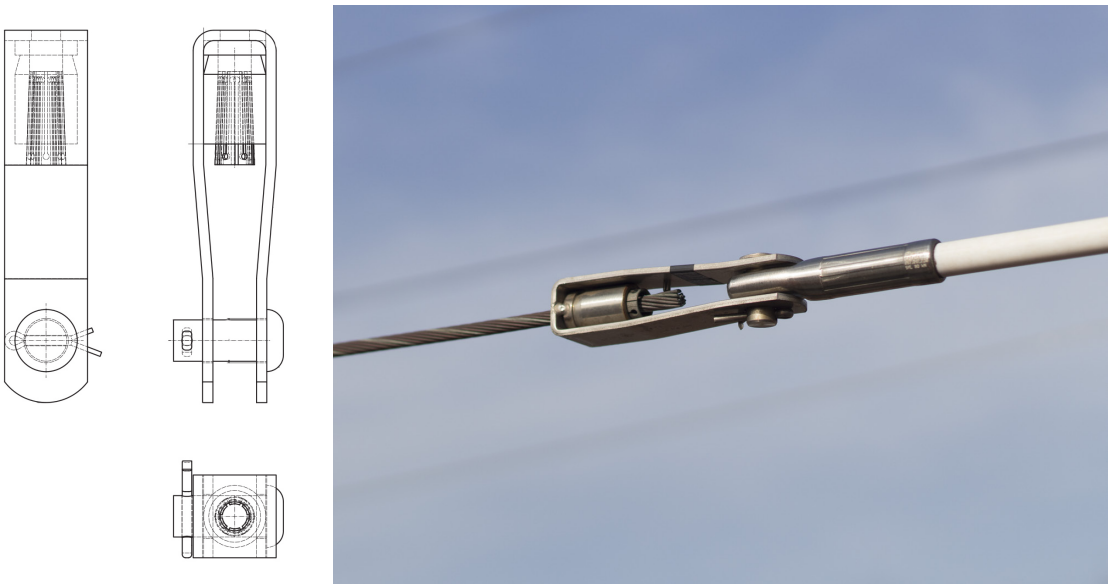


Figure 228: Forked collar socket for 19/2.1 catenary termination

[157] An installation video is available online at youtu.be/B7zXcSiIPc8.

It is often necessary to join two tensioned wires together – for instance when joining RCs, EWs or ATFs in long runs, splicing contenary into catenary (section 10.8), or as part of a repair after a dewirement. For many years the standard way to do this was via a *compression splice*. This comprises an double-ended copper or aluminium sleeve (to match the wire) which is internally coated with a conductive grease (to keep out water), into which the wire ends fit. A compression tool is then used to create a series of crimps to hold the wires[158].

Figure 229: Compression splice used for splicing bare RC

This process is time-consuming and easy to get wrong, and so in recent years compression splices have been replaced by double-ended *conical couplers*. These comprise a CuNiSi barrel and AlBz collet with internal spring-loaded teeth which point away from the direction of tension. The wire simply push-fits into place, and as the wire is tensioned the teeth bite into the wire and secure it. These fittings are much easier and quicker to fit, and are more reliable in use.

Figure 230: Conical coupler splice joining 120mm^2 contact wire acting as contenary (left) to 19/2.1 catenary (right)

None of the above solutions are suitable for joining two lengths of contact wire together – something which is done only as part of a repair, since it introduces a potential failure mode into the most sensitive part of the system; or for terminating an in-running contact wire at a section insulator (section 11.6.1) or in-line neutral section (section 11.6.3). Various designs are available, but all use the contact wire groove (section 11.16.1) to

[158] An installation video is available online at youtu.be/K7A_awOllYA.

make a connection.

The *battleship splice*, so-called because of its (alleged) resemblance to a warship, has been used since the 1960s. A set of inclined bolts bear down on the top of the contact wire, cutting into it to transfer the tension to the casting. The bolts are then wired together to prevent loosening.

Figure 231: Battleship contact wire splice

This was superseded by the *butt splice*, which uses two symmetrical CuNiSi castings clamped via a set of opposing screws. It relies on the friction between the clamp and the contact wire groove.

Figure 232: Butt splice for contact wire

Special arrangements are required when a wire run is converted to a tail wire arrangement (section 11.4.5) or tensioned via a single tensioner (section 11.3). The contact wire and catenary are terminated at each end of an *equalising plate* (also known as a *balance plate*) and the tail wire or tensioner connected at the centre.

Figure 233: Equalising plate in UK1 wire run; note the unequal lengths used to split the 11.9kN/8.56kN UK1 tensions

The ratios of the lengths of the equalising plate arms determines how the tension provided by the tensioner is shared between the contact wire and catenary; equal lengths provide equal tensions, and unequal lengths are used to split the tension unequally between the wires.

11.17.2. Untensioned Connectors

It is often necessary to connect an untensioned wire to a tensioned one – for instance at jumpers (section 11.4), midpoint connections (section 10.4.2) and switching locations (section 11.7). There are a number of ways of achieving this.

Parallel Groove (PG) clamps use a similar arrangement to the butt splice overleaf. They come in two variants; one which connects two stranded wires together by clamping around both, and another which clamps a stranded wire to a contact wire (again using the groove).

Figure 234: PG clamp connection for jumper onto contact wire

An alternative method which has been used for connecting aluminium wires together is the *Ampact wedge connector*. This uses an aluminium wedge which is driven between the two wires as they are held in an

aluminium C-sleeve. The required amount of compression is achieved by firing a small explosive charge from a specially-designed gun[159].

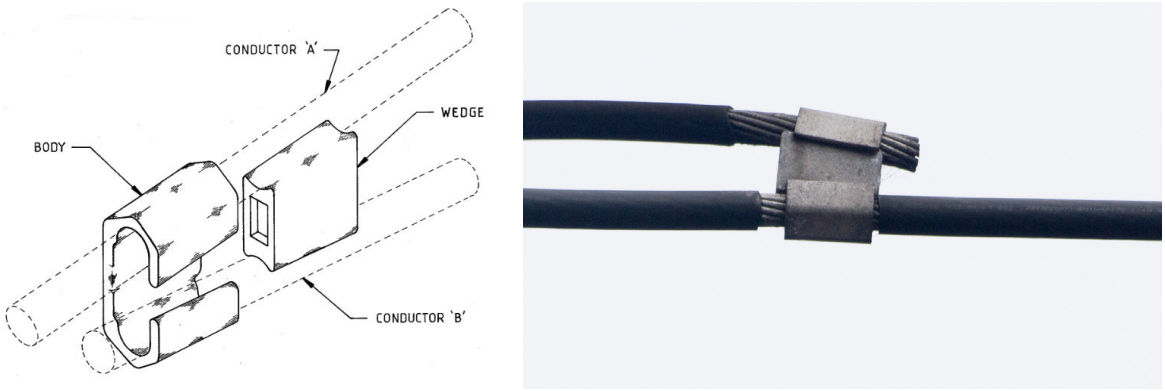


Figure 235: Ampact wedge clamp connection onto RC

In the UK these have been deprecated in favour of a version which uses shear bolts and so does not require specialist explosive charges.

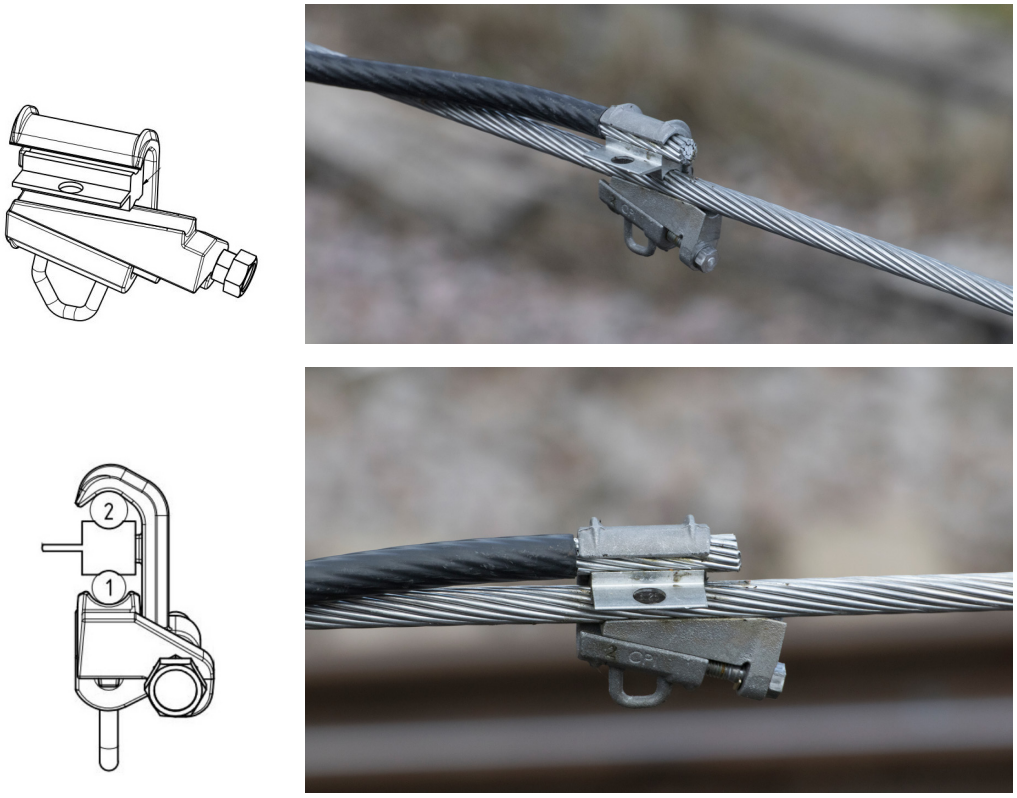


Figure 236: Wedge connector – shear bolt type

Special measures are required when connecting wires of dissimilar metals together, to prevent cathodic corrosion. In this case a *bimetallic lug* is inserted between the two wires. This is a specially fabricated assembly, which comes in various forms, each including two metals (typically aluminium and copper) friction welded together. These can be used in conjunction with PG clamps or wedge clamps to facilitate joining of copper jumpers to AWAC (section 11.16.3) or aluminium feeder wires to copper RC (section 10.4.1).

[159] An installation video is available online at youtu.be/6TmdxEwLWhI.

Figure 237: (top to bottom) Bimetallic connections; copper jumper onto AWAC, AWAC to contenary; note blue markers denoting copper end of lug

When arranging these types of connections, it is important to arrange the aluminium wires and fittings above the copper ones; otherwise any acidic rainfall (a feature of areas with high pollution) will wash copper sulphate (*copper wash*) onto the aluminium, causing corrosion.

11.18. Insulators

Insulators are required to separate live parts of the system from earthed parts, or to separate electrical sections. The insulators chosen for the system must meet the following requirements:

- Sufficient electrical strength (section 10.8) for electrical loads, faults, and lightning strikes, as determined by the insulation coordination process;
- Sufficient mechanical strength for the location and use – including tension, bending or torsional loads;
- Sufficient creepage path for the environmental contamination at the location;
- Sufficient durability to withstand vandalism;
- Wherever possible, be self-cleaning under the action of rain and wind.

The electrical strength is chosen to match the system voltage (section 10.1.1). The *creepage path* is the distance measured around the outside of the insulator, and the required distance may be achieved by means of ribbed sections (*sheds* – so called because they are designed to shed water), or they may simply be *long rod insulators*.

11.18.1. Materials

The material used for an insulator is dependent on placement, cost and environmental factors. Hard porcelain has historically been favoured in the UK due to its cost-effectiveness and ease of fabrication. However these are prone to vandalism (especially by air rifle) and to explosive failure if moisture ingress occurs. Some porcelain insulators have a hollow gas-filled core, but these are prone to leakage and subsequent failure by the same water ingress mechanism.

In recent years *shed protectors*, comprising a rubber sleeve which fits tightly around the shed, have been added to porcelain insulators. These help the sheds to withstand vandalism, and can hold together a damaged insulator.

Pre-stressed glass is used extensively in Europe, being more robust than porcelain, but also more expensive.

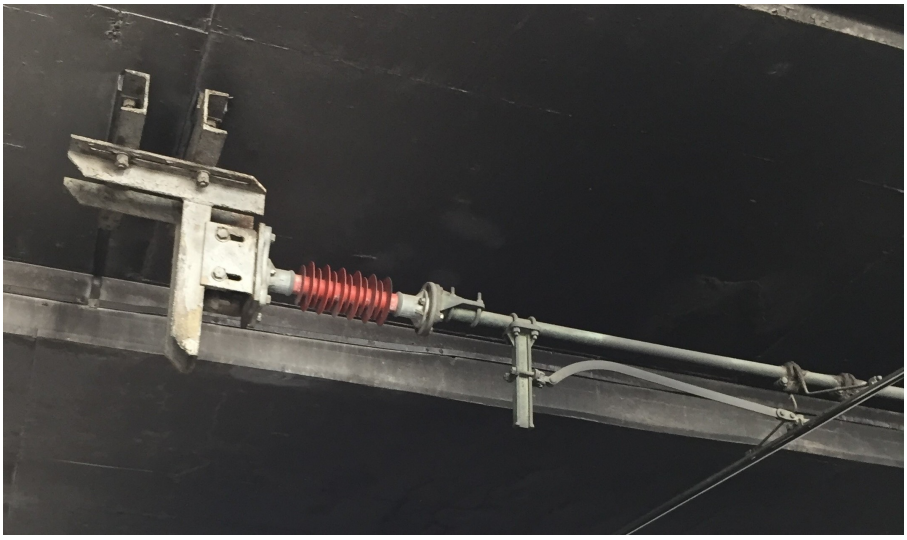


Figure 238: Lightweight shedded polymeric 25kV insulator. Manchester, UK

Plastic (or *polymeric*) insulators – comprising a Glass Fibre (GF) and epoxy resin core with silicone sheds - are now standard in the UK, as they are lighter and smaller than their porcelain or glass counterparts, and are naturally *anti-vandal*, since the sheds deform rather than break on impact. However polymerics bring new problems – sheds can deform if not stored correctly prior to construction, and some birds will eat the polymers (section 11.19).

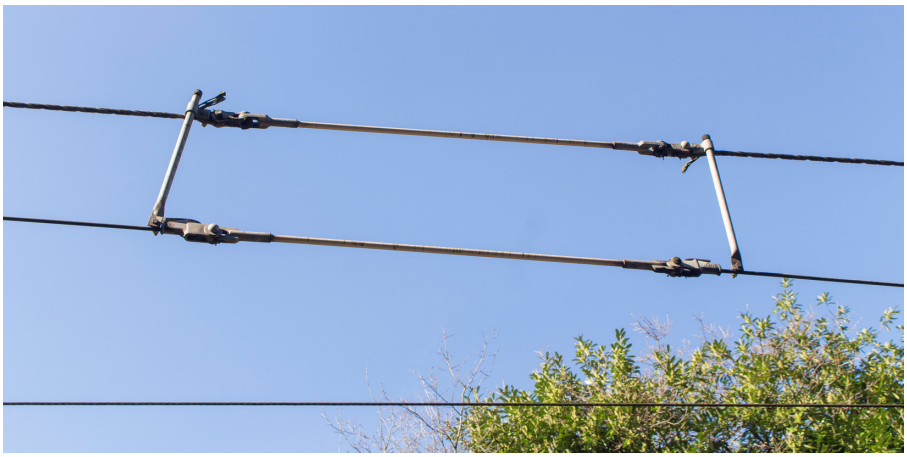


Figure 239: Polymeric 25kV rod tension insulators, with anti-torsion bars. Edgbaston, UK

Plastic insulating materials may also be formed into rod insulators. These also use silicone over a GF/epoxy core, and are used at locations where clearances to the pantograph are small, and a shedded insulator would be too large. When placing rod insulators into stranded wires, it is important to control the natural torsion which a wound wire applies to the insulator, since rod insulators are very weak in torsion. This is usually managed by means of *anti-torsion bars* which are clamped to the catenary and contact wire either side of the insulators. *Glass Fibre* insulators can withstand small bending loads, although with a certain amount of flexure. This property is exploited when glass fibre insulators are used as *bridge arms* (section 11.10.9).

Plastic materials are also used extensively for *rope insulators* on tram systems.

11.18.2. Mechanical Requirements

The mechanical load requirements of the insulator depend on the use. *Tension insulators* are designed to take a purely tension load. They are used as *cut-in insulation* in conductors, and as vertical catenary supports.

Figure 240: (l-r) Insulator types; porcelain cap-and-pin type, porcelain post type

They may be formed as individual shed components, joined together by means of a *cap and pin* arrangement to form an insulator of the required electrical strength.

Post insulators are designed to take bending and compression loads, and are used to support feeder wires and support catenaries.

Some *switching insulators* are designed to take a torsional moment and are used in torsion-tube operated switches. Others are used in push-rod switches and do not need to withstand torsional moments.

Glass Bead Insulators are formed of glass beads threaded onto a rod, and they are used in circumstances where an insulator is required in the in-running contact wire; for instance, at inline neutral sections (section 11.6.3). This type of insulator needs regular cleaning to remove carbon deposited by the pantograph, and their use is therefore minimised.

Figure 241: Suspension insulator for ATF. Cholsey, UK

Suspension insulators (colloquially known as *danglers*) are used to support auto-tensioned (section 11.3) wires which only require a small range of movement, typically near the midpoint anchor (section 11.10.11) or fixed anchor (section 11.10.10) locations. They are also used to support fixed termination ancillary conductors, especially ATFs (section 10.4.3), as they help to equalize the wire tension between spans without imposing high bending moments on individual insulators.

11.19. Protection Against External Factors

A number of external factors can result in damage to OLE, and a range of measures are adopted to mitigate these.

11.19.1. Vehicle Damage

It is often necessary to place structure foundations (section 11.11) within areas accessible to road vehicles, such as a station car park, access road or RRAP approaches (section 19.2.1). This makes the critical interface between the foundation and the structure vulnerable to accidental damage. Crash barriers are often fitted at these locations.

Figure 242: Armco vehicle protection barrier. Severn Tunnel Junction, UK

11.19.2. Wildlife Deterrents

All OLE systems suffer to a greater or lesser extent from interactions with wildlife - especially, but not exclusively, with birds. These interactions often result in damage to the OLE and injury or death for the animal. Since many countries offer legal protections to wildlife, infrastructure managers are often obliged to take reasonable steps to prevent harm to animals, as well as protecting the system from damage. Many systems adopt deterrent measures to dissuade birds from flying into conductors or roosting in areas with small air gaps, and some systems attempt to dissuade climbing animals from approaching live parts.

The extent to which animals are a problem, and the type of problems they cause, are a function of the local environment; and in some countries, the problem is highly seasonal. The following are just some of the problems encountered around the world, and the mitigation measures in place:

- United Kingdom: low-flying water birds can fly into conductors, and so bird scarers are attached to the outermost conductors in areas with aquatic habitats;
- Australia: administrations have reverted to using glass insulators, since the local parrots were eating the polymeric insulators;
- India: eagles and other large birds cause significant problems by nesting within lattice structures and around lineside switching. Monkeys often climb from adjacent trees onto OLE and have been known to eat polymeric insulators.

Figure 243: (l-r) Bird scarer attached to aerial earth wire, bird's nest in a lattice structure, birds roosting on OLE and anti-monkey spikes on insulators

11.19.3. Anti-Vandalism Measures

Vandalism and trespass is an unfortunate reality in many parts of the world, and railways take steps to guard against interference with the safe and reliable operation of OLE systems, as well as protecting people from the consequences of their own actions. Typical measures deployed include:

- Polymeric insulators (section 11.18);
- *Anti-climbing guards* (ACGs) or shrouds on vulnerable structure masts;
- *Anti-walking guards* on vulnerable portal and TTC booms.

Figure 244: (l-r) Anti-climbing guard, anti-climbing shroud, anti-walking guard

11.19.4. Icing Mitigations

Railways in colder climates suffer from significant *ice accretion*; while the additional load on structures can be mitigated by appropriate loading allowances (section 11.9.2), accretion on the contact wire can cause loss of contact, damage or increased wear to the pantograph carbons (section 11.1), or in extreme circumstances, parting of the wire.

Figure 245: (l-r) Extreme ice accretion on OLE, early morning frost arcing

Some administrations deploy trains with special scraping pantographs to combat this; others rely on running ordinary electric trains at night in an effort to prevent ice forming on the wire. Still others utilise *Joule-effect defrosting*, where a resistance is switching into the OLE circuit, ensuring that some traction current flows even when no train is in section, so providing a degree of electrical heating; however this is an expensive solution to the problem.

12. Signage

OLE is typically provided with a number of signs to:

- Identify the names and locations of equipment;
- Provide a means of identifying location during safety-critical communication;
- Ensure that the right piece of equipment is being operated or worked on;
- Give the driver of a train critical information or instruction relating to the traction system;
- Warn of electrical dangers at locations accessible to staff and the public.

The following signage examples are all from the UK; other administration use different depictions and conventions to convey the same information.

12.1. Asset Signage

These signs are provided as a means to identify the names and locations of equipment.

12.1.1. OLE Structure Signage

OLE structures are generally given a unique identification number. In the UK the historical convention has been to use a combination of route code and along-track location. The structure number is in the form [Route code][Unit]/[Number]. The route code comprises one or more letters[160].

The unit is either the mile (historically) or kilometre (more recently) within which the structure is located, and the number is a simple increment within the unit. For instance, the first structure at the zero point at London Liverpool Street is B00/01; the route code is B, and the structure is the first in the '0' mile. Subsequent structures are B00/02, B00/03... until the 1 mile mark is reached. The first structure past this mark is B01/01, then B01/02 and so on.

Figure 246: Structure number plate for the 25th structure in the 29 mile section of the GE mainline. Chelmsford, UK

Where new structures are introduced on an existing electrified route, a letter suffix is used; so if a new structure is required between B01/04 and B01/05, it would be numbered B01/04A. A second new structure at this location would be numbered B01/04B, and so on.

More recently this system has been replaced by a system which uses the Engineer's Line Reference – a more widely used route code in the UK – and the along-track kilometrage. For instance, an OLE structure at Didcot on the GWML is numbered MLN85.507 – MLN being the route code and the structure being 85.507km from Paddington.

[160] A comprehensive list of UK route codes is available online at Phil Deaves' railway codes website www.railwaycodes.org.uk/electrification/mast_prefix0.shtm.

12.1.2. Wire Run and Section Insulator Signage

UK installations are provided with section numbers at Section Insulators (section 11.6.1), and (more recently) with wire run marker plates at anchor locations (section 11.10.10).

Figure 247: Section Insulator with number plate. Edinburgh, UK

12.1.3. Switch Signage

All OLE isolators (section 11.7) are provided with a unique number which is marked at the switch location and referenced on the isolation diagrams and instructions (section 18.4.13). Numbering for mid-section switches takes the form:

[*subsection number*]/[*number of switch in subsection*]

Switches bridging two sections take the form:

[*subsection 1*]/[*subsection 2*]

Figure 248: Switch number plate for switching joining subsection 430D to 431F. Stratford, UK

12.1.4. Designated Earth Positions

Marker plates are provided at DEP locations (section 10.12.1).

Figure 249: DEP plate. Darlington, UK

12.2. Operational Signage

A number of signs are provided to assist train drivers to carry out their duties.[161]

12.2.1. Neutral Section Signage

A *Neutral Section Warning Board* is placed around 1.6km on approach to a neutral section location (section 11.6.3), to give to driver advance notice of the need to shut off power.

Figure 250: (l-r) Neutral section signage boards; AJ01 Neutral Section Warning, AJ02 Neutral Section Indication, AK205 Rear Clear of Neutral Section Board (all with long CWNS indications)

A *Neutral Section Indication Board* is provided immediately on approach to the neutral section to denote the location of the neutral section.

A *Rear Clear of Neutral Section Board* is provided at a position beyond the neutral section to indicate that all pantographs on the train are now clear of the neutral section.

12.2.2. Power Changeover Signage

These signs are provided wherever trains must change between different electric traction systems, or from electric to diesel traction.

[161] GIGN7634 "Index for Lineside Signs"; Issue 1.1, July 2019; RSSB; section G2.2.6. Signs themselves are found by searching Railway Group Standards Online using appropriate search terms.

The *Warning of Traction System Changeover Board* is placed on approach to an electrical changeover from one system to another. This applies equally to 750V DC third rail to 25kV AC OLE, or vice versa.

The *Traction Changeover to 25kV AC Board* is placed at an electrical changeover from any other system to 25kV AC OLE.

The *Lower Pantograph Board* is provided at all locations where a bi-mode electro-diesel train is required to switch from electric power to diesel, or a dual-voltage train is required to switch from overhead power to 3rd or 4th rail power.

Figure 251: (l-r, top to bottom) Operational signage boards; AJ04 Warning of Traction System Changeover, AJ05 Traction Changeover to 25kV AC, End of Traction Changeover Zone, AJ03 Lower Pantograph (with train type label), AJ03 Lower Pantograph (with diverging route label)

The *Traction Changeover to 750V DC Board* is placed at an electrical changeover from any other system (typically 25kV AC in the UK) to 750V DC third rail.

The signs above are shown in permanent locations; but temporary situations (such an obstruction on the overhead line) often require electric trains to coast through a section of railway, relying only on its inertia until operational OLE is reached at the other end. This means that all pantographs must be lowered for a short period, and for this purpose signs are temporarily placed sequentially along the railway as follows[162]:

- Advance lower pantograph board;
- AJ03 board;
- obstruction;
- AJ05 board;

[162] GE-RT8000-AC "Rule Book: AC Electrified Lines"; Issue 6, September 2020; RSSB; section 15.5.

- End of traction changeover zone board.

This mode of working is limited to 20mph in the UK. For planned works, *High Speed Coasting* at linespeed may be authorised, allowing a longer section of OLE to be out of use, but requiring correspondingly higher starting speeds.

12.2.3. Limit of Electrification Signage

A *No Access to Electric Trains* sign is provided at all locations where an overhead electric train could be mistakenly signalled or shunted onto a line not provided with OLE. Complex locations with a mix of permissible and non-permissible routes for electric trains are provided with additional explanatory text.

Figure 252: Limit of Electrification boards. Didcot, UK

12.3. General Safety Signage

A number of different types of warning sign are provided at locations where railway workers or members of the public are in proximity to live parts.

Figure 253: General electrical hazard sign on overbridge. Brinkworth, UK

13. Types of UK Equipment

There are approximately 100different types and subtypes of OLE present in the UK, including tram and light rail systems. The type refers to the generic system, such as Mark 1 or Mark 3b. The subtype refers to the suspension and tensioning system, and the tensions in each wire. A type may have many subtypes; for instance Mark 1 has simple and compound, auto-tensioned and fixed termination variants.

The complete list of OLE types in the UK can be found in Appendix D.

Care must be taken when modifying existing equipment, to determine the type in use and ensure that compatible parts are used.

13.1. Basic Design Ranges

A *Basic Design Range* is a set of drawings which define the components, materials, geometry and parameters of a given OLE system. Each range may contain one or more types of equipment. The allocation designer applies these to a given location in accordance with the requirements of that location.

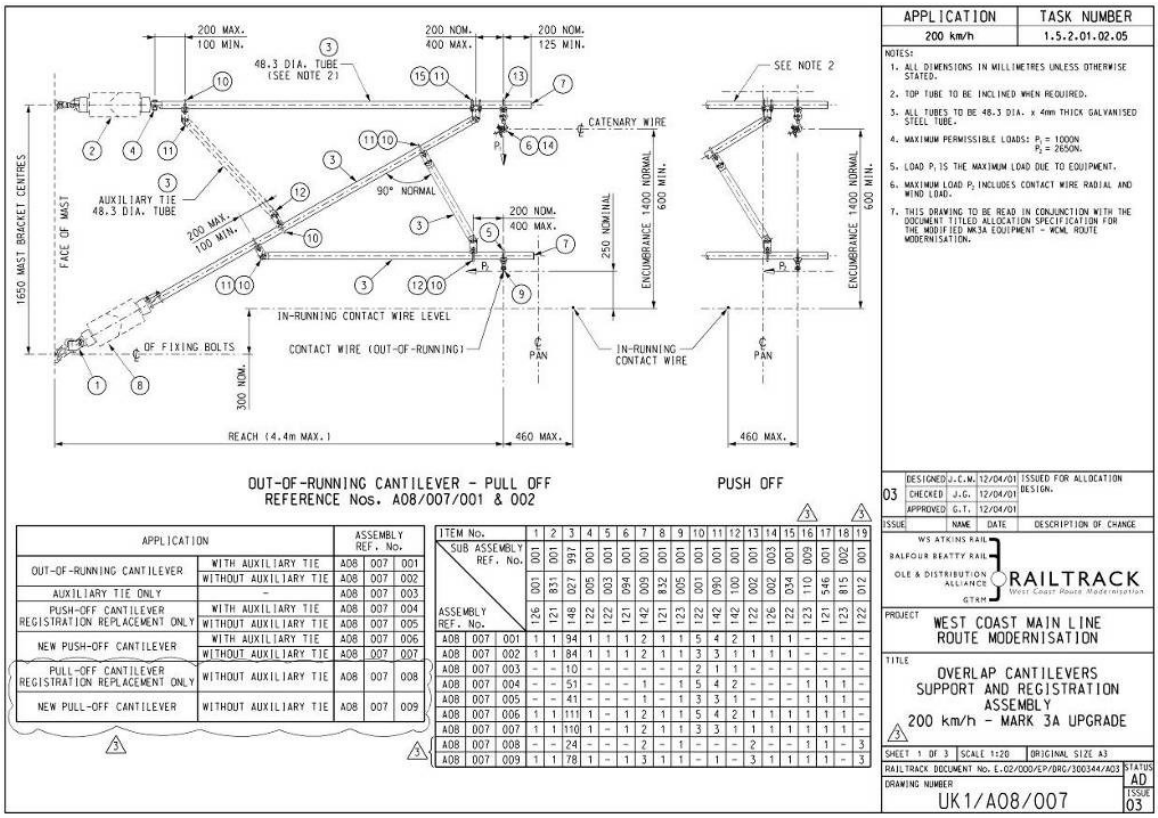


Figure 254: Typical basic design drawing

The following sections give an overview of the various basic design ranges in use in the UK. Each country will have a set of basic designs in this manner; these are developed appropriate to the technology available at the time, and to the performance requirements of the system.

13.2. Historic Design Ranges

These ranges were developed in the UK during the period before standardisation and metrication was introduced, but they remain in use on legacy routes.

13.2.1. The MSJ&A Range

The *Manchester South Junction and Altrincham* (MSJ&A) railway is one of only two routes in the UK to have been energised at three different voltages; it was electrified at 1500V DC in 1931, then converted to 25kV AC in 1971, and then in 1991 to 750V DC to become part of the Manchester Metrolink tram system. Although the original OLE did not survive conversion to 25kV, many original structures remain and are the oldest in the UK. Much of the 750V DC system still uses the previous Mark 3 (section 13.3.1) 25kV support and registration arrangements and insulators.

Figure 255: 750V DC OLE for trams on original MSJ&A portals with 25kV insulators. Timperley, UK

13.2.2. The GE/MSW Range

The *Great Eastern* (GE) range was developed by London & North Eastern Railways (LNER) and subsequently BR, and was first installed in 1949 for the electrification of the lines out of Liverpool St at 1500V DC. It was then used on the *Manchester to Wath and Sheffield* (MSW) route in 1954. The range was updated to reflect the conversion of GE lines to 6.25kV, and the subsequent conversion of both GE and the remaining section of MSW to 25kV AC. GE/MSW equipment, where it remains, is the oldest working type in the UK. However the amount in service is rapidly decreasing as routes are upgraded to GEFF equipment (section 13.4.2).

Figure 256: GE compound OLE and anchor portals. Shenfield, UK

The range is imperial and robustly engineered, using large quantities of copper, which was a cheap material at the time. The range uses painted steel fabricated portals and planted masts, with a large amount of fabrication carried out on site. Most structures are MIR type, with spanwire portals used in complex areas and sidings. The system had a large quantity of fixed termination equipment on running lines – most of which has now been upgraded to the GEFF auto-tensioned system – as well as auto tensioned equipment for higher speeds. The contact wire, auxiliary and catenary are of a very large cross section, reflecting the original requirement to carry DC currents; this, coupled with the low tension, means system heights are large and supports are substantial. The insulation has been upgraded to 25kV standards, but the configuration of the original DC catenary supports means that electrical clearances are small by modern standards.

The range is no longer available for design use.

13.2.3. The SCS Range

The *Shenfield-Chelmsford-Southend* (SCS) range was first installed in 1956 as an extension to lines electrified using the GE system. The range was also originally 1500V DC, and was updated to reflect the conversion of GE lines to 6.25kV and then 25kV AC. The range replicated most of the features of GE equipment, including heavy contact wire, fixed termination and compound suspension. As with GE equipment, the insulation has been upgraded to 25kV standards. The range is no longer available for design use.

Figure 257: SCS compound OLE on cantilevers braced for poor ground conditions. Wickford, UK

13.2.4. The Mark 1 Range

The *Mark 1* range was developed by BR and Balfour Beatty in the early 1960s for the first phases of WCML electrification. Like the GE range, the assemblies are imperial and use copper. The range also uses painted steel fabricated portals and planted masts. All structures are MIR type, with catenary pulleys. Again, system heights are large (nominal 1980mm). For the first time mainlines were equipped with auto-tensioned equipment, setting the standard for all later equipment types. Mark 1 equipment originally came in simple, compound and stitched variants, but the stitched version was soon abandoned. Simple and compound equipments remain in widespread use today. Network Rail has recently developed an upgrade range for Mark 1, UKMS R1 (section 13.4.5); and this will be used for midlife renewals (section 17.1) in the coming years.

Figure 258: Mark 1 portal - note the retrofitted UK1 catenary supports. Watford Junction, UK

The range is no longer available for design use.

13.2.5. The Brown Boveri Range

The *Brown Boveri* range was specified by Pirelli for the second stage of the Glasgow South Suburban electrification scheme, as an alternative to Mark 1 equipment. However this scheme was subsequently taken over by BICC who instead specified Mark 2 equipment (see below). As a result Brown Boveri equipment is confined to the Neilston branch of the Glasgow network. This equipment is unique in the UK in using a simple stitched (section 11.2) configuration.

Figure 259: Brown Boveri Cantilevers with stitch wire (arrowed). Whitecraigs, UK

13.2.6. The Mark 2 Range

The *Mark 2* range was a short-lived development of the Mark 1 range, and was installed in the Glasgow suburbs in the 1960s. It pioneered the use of galvanised steel support and registration equipment. It remains in use on these lines but is not available for design use.

Figure 260: Mark 2 portal. Bishopton, UK

13.2.7. The Tyne & Wear Metro System

This system was developed in the late 1970s for the electrification of the Tyne and Wear Metro. The system is configured for use as a 1500V DC system, using simple auto-tensioned equipment with a mix of lightweight cantilever and headspan structures. Some heavily loaded sections use twin contact wire and/or twin catenary to minimise volt-drop.

13.3. The OLEMI System

The *OLE Master Index* (OLEMI) was initiated in the early 1970s in response to the requirement for cheaper OLE builds, and was still being added to until quite recently. It was developed by BR, is now owned by NR, and consists of approximately 13000 drawings. The OLEMI was developed as a modular system, where a single component can carry out several tasks. It is also a metric system, and was initially developed with mechanically dependent supports in the form of headspans. MIR assemblies were later added to the range. The range contains the Mark 3, Mark 3a, Mark 3b, Mark 3c, Mark 4, Mark 5 and UK1 ranges, and metric conversion assemblies for Mark 1. OLEMI schemes include the second phase of WCML electrification, the ECML and the southern section of MML. In an effort to reduce structural steelwork costs, the standard system height was reduced (as low as 900mm for Mark 3b).

The OLEMI is available for use in modifications and extensions to existing OLEMI routes, but is out of favour for new electrification due to its numerous failure modes; it is mature, and no longer subject to update.

13.3.1. The Mark 3 Range

The *Mark 3* range was developed in the late 1960s, and introduced headspans in a bid to reduce both capital costs and the ongoing maintenance that painted portals need.

It also pioneered the use of pre-sagged simple equipment (section 11.2) in the UK. The range maximised the use of galvanised steel, in lieu of copper, since prices had risen steeply by this time. Copper clad steel wires were used for headspans, but these have since suffered corrosion issues and are now being replaced (section 11.16.6).

Figure 261: Mark 3 spanwire TTC and single cantilevers. Enfield, UK

13.3.2. The Mark 3a Range

The *Mark 3a* range was introduced in the early 1970s as an evolution of Mark 3. It also used headspans, but introduced bridles at the catenary support in order to reduce catenary wear at pulleys. In a further effort to reduce the amount of copper used, AWAC (section 11.16.3) was introduced. Midlife corrosion issues mean that this wire is now being replaced on Mark 3a and Mark 3b installations.

Figure 262: Mark 3a headspan. Harringay, UK

13.3.3. The Mark 3b/3c Range

The *Mark 3b* range continued the use of headspans and AWAC, but introduced bolted base masts to help speed up construction. Mark 3c was introduced to allow a copper catenary to be used instead of the now-problematic AWAC variant, but is otherwise identical. In the 1990s MIR portal assemblies were also added to the Mark 3b range.

Figure 263: Mark 3b headspan. Peterborough, UK

13.3.4. The Mark 3d Range

The *Mark 3d* range was developed in the mid 2000s as an upgrade range for existing OLEMI equipments, particularly for use on the ECML. The range is designed to rectify specific failure modes in Mark 3a and 3b equipment, including problems with AWAC (section 11.16.3) and solid dropper failures (section 11.16.4).

13.3.5. The Mark 4 Range

The *Mark 4* range was developed in the 1970s as a high speed compound system to support the introduction of the APT (section 8.5) on WCML. It was never implemented.

13.3.6. The Mark 5 Range

The *Mark 5* range is a heavy current version of Mark 3c, using 150mm^2 copper contact wire. It was used only at Dollands Moor freight yard as part of the Channel Tunnel construction.

13.3.7. The UK1 Range

The *UK1* range was developed in the late 1990s in response to the requirement under *West Coast Route Modernisation* (WCRM) to raise WCML linespeeds. The existing Mark 1 and Mark 3a equipments on the route were not adequate for these speeds, and so an upgrade range was required. The range covers the upgrade of Mark 1 and Mark 3a equipment to either 200 or 225km/h, although only the 200km/h upgrade was used.

The range was developed by Balfour Beatty and Atkins, is modular and uses aluminium MIR assemblies derived from continental best practise. It is used at existing Mk1/Mk3a locations and for new schemes. The range is now mature, and is not subject to updates.

Figure 264: UK1 equipment. Ledburn Junction, UK

13.3.8. The ATF Range

The ATF range was introduced around 2000 for the upgrade of the WCML to Auto Transformer feeding. It contains a range of AT feeder support assemblies and bridge route solutions. It is mature, and is being used on the Crossrail project and Paddington to Stockley auto transformer upgrade.

Figure 265: Auto Transformer Feeder support. Greenholme, UK

13.3.9. Other Assemblies

A number of other arrangements exist in the UK, which have not been included in an approved design range, and a therefore not officially available for new use. For instance, under the Euston Remodelling contract on WCRM, new Mk1 FT assemblies were introduced. These are not part of OLEMI or UK1.

13.4. Modern Mainline Systems

13.4.1. The SICAT Range

The *SICAT* (Siemens Catenary) range was introduced to the UK in 2005 for the Larkhall – Milngavie project, and was subsequently used on the Shields – Gourock project. It uses Siemens SICAT SA medium speed equipment, with aluminium alloy cantilevers and extensive use of side-bolted connections rather than clevises.

Unlike other UK systems, heel settings are variable depending on radial load, and so setup requires more care.

Figure 266: SICAT portal cantilevers. Paisley, UK

13.4.2. The GEFF Range

The *GEFF* (Great Eastern Furrer+Frey) range was developed by Network Rail and Furrer+Frey for the Great Eastern route upgrade. The range was a response to the poor performance of the ex-1500V DC Fixed Termination equipment (section 13.2.2) on the route from Liverpool St to Shenfield, and provides a lightweight modern sagged simple AT equipment for the existing GE structures. Only the structural elements of the original GE equipment are retained.

The range was based on Swiss practice, and contained a number of first-of-type arrangements for the UK, including double boom anchor portals and *Single Insulator Cantilevers* (SICs) which give a reduced component count and smaller live envelope, and are easier to install and adjust than conventional cantilevers.

Figure 267: Single insulator MIRs on GEFF equipment. Bethnal Green, UK

Figure 268: Double boom anchor portals for GEFF equipment. Bethnal Green, UK

13.4.3. The Series 2 Range

The *Series 2* range was introduced as part of the National Electrification Programme in the late 2000s to provide a reliable medium speed sagged simple OLE system which comprehensively addressed the shortcomings of OLEMI systems.

Initially developed for 160km/h, it is a development of Mark 3c, with modern support arrangements including both Bonomi and Furrer+Frey cantilevers.

Series 2 has now been extended to cover speeds up to 200km/h and provide NTSN-compliance for multiple pantographs, as part of the UKMS catalogue (section 13.4.5).

Figure 269: Series 2 Bonomi cantilever. Glasgow, UK

13.4.4. The Series 1 Range

The *Series 1* range was introduced as part of the National Electrification Programme in the early 2010s as a 2x25kV auto transformer configuration, providing reliable NTSN-compliant, multiple pantograph 225km/h-rated sagged simple system which comprehensively addressed the shortcomings of OLEMI systems. The system has been installed on the Great Western Mainline and includes a number of innovations designed to improve electrical safety, increase ALO working (section 19.12.3) for construction and maintenance staff, and improve installation productivity during short possession windows.

Figure 270: Series 1 land-and-leave two track cantilever with reduced encumbrance SICs. Moreton, UK

The system was developed by Network Rail and Furrer+Frey, and develops some of the arrangements used in the GEFF range (section 13.4.2). The system pioneered the use of single span overlaps without anchor spans (section 11.4.3) and was the first to extensively use *land-and-leave* structures which have rapid installation connections between masts and booms.

Series 1 has now been incorporated in the UKMS catalogue (section 13.4.5).

13.4.5. UK Master Series

UK Master Series (UKMS) was developed in the mid 2010s as a single OLE design catalogue for Network Rail, and incorporates Series 2 (renamed as *UKMS100* and *UKMS125*), Series 1 (renamed as *UKMS140*), and UKMS R1, an upgrade range for Mark 1 equipment (section 13.2.4).

13.5. Other Systems

All of the aforementioned systems operate on UK mainline infrastructure and are owned and administered by Network Rail. The following systems are owned by private operators.

13.5.1. The Alstom Cariboni Range

The *Alstom Cariboni* range was introduced in 2018 for those surface sections of the Crossrail project in London which are not owned by Network Rail. The range adopts typical French componentry with conventional cantilevers and portals, and support and registration arrangements have much in common with the High Speed One range (section 13.5.3); but also adopts elements of UK best practice such as spring tensioners (section 11.3).

Figure 271: Alstom Cariboni twin cantilever structure. Custom House, UK

13.5.2. The Channel Tunnel Range

The *Channel Tunnel* range was installed inside the Channel Tunnel between the UK and France in 1994. Although nominally a Balfour Beatty design, it was influenced by French high speed practice, despite the tunnel being limited to 160km/h. It uses sagged simple equipment with conventional galvanised steel cantilevers and portals, and glass insulators.

Figure 272: Channel Tunnel equipment. Coquelles, France

13.5.3. The High Speed One Range

High Speed One uses the only true high speed OLE system in the UK. It was designed by Amec Spie and installed in the early 2000s. It comprises pre-sagged simple equipment (section 11.2) configured for auto transformer feeding (section 10.4.3).

The configuration is typical of French high speed systems, with galvanized steel structures carrying inclined cantilevers, deep curve registration arms (section 11.13.2) and opposing cantilevered ATF hangers. It operates at speeds of up to 300km/h.

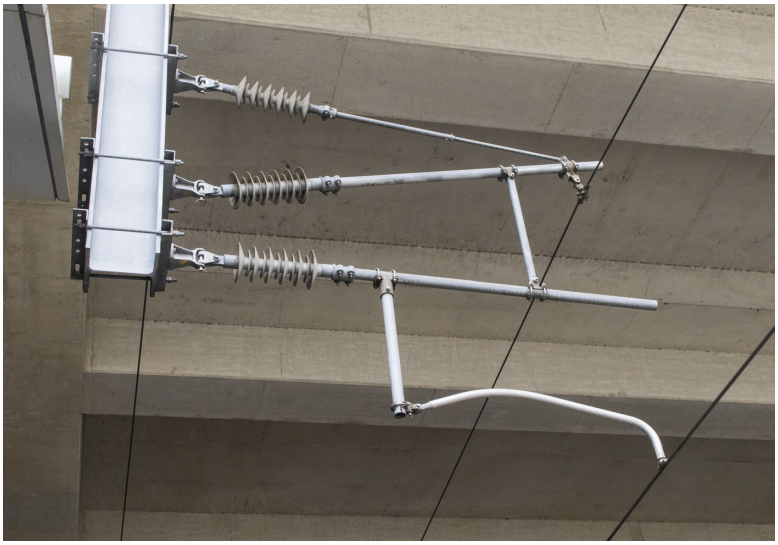


Figure 273: High Speed One cantilever. Stratford, UK

14. Tram and Trolley Systems

Trolleybus systems (section 9.2), as well as a few older tram systems[163] take a different approach to current collection, using *guided trolley pole collectors* rather than pantographs. For trolleybus systems the double pole nature of the system means that using trolley pole collectors is the only practical option, since the vehicle must be able to change lanes and pull over to the kerb to transfer passengers. Trolley OLE allows the vehicle to occupy up to three lanes using a single set of wires.

Figure 274: Articulated trolley bus. Vancouver, Canada

A full description of the design and operation of trolley systems is beyond the scope of this book, but this section summarises those features of trolley systems which are significantly different to those of conventional OLE[164].

The key advantage of using a guided pole rather than a pantograph is that contact wire position no longer needs to be strictly controlled relative to the vehicle. This has obvious advantages for unguided trolleybuses, but was also useful for early tram networks, which used a dense network of tracks. Removing the strict geometrical relationship between track and OLE means that more flexible tram wiring arrangements can be adopted, with groups of wire runs clustered in the centre of multiple tracks. For early tram systems, the pole arrangement placed the contact point well to the rear of passengers on an open-top tram – an important consideration given that debris could fall from the wire under the action of the head. Finally, the flexibility of wire position was useful for routes with open deck trams and low bridges – allowing the wire and pole to be slewed to the side of the tram as wire height reduced, to maintain safe separation of live parts from passengers.

[163] Many of these tram systems have since been converted to use pantographs, and only a few remain in use.

[164] en.wikipedia.org/wiki/Trolley_pole.

14.1. Trolley Collector Poles

The *trolley collector pole* takes the form of a long, flexible pole mounted on a spring- or pneumatically-actuated carrier or a mast on the roof of the vehicle[165]. Modern poles are typically made of aluminium[166].

A *collector head* is mounted at the top of the pole; the carrier exerts an upward force on the pole, and the collector head rests on the underside of the contact wire. The pole deflects elastically, and this ensures a continuous contact force is maintained on the wire. Modern trolley poles are provided with a traction cable running down the centre of the pole, whereas older metal poles were often live and insulated from the tram roof or deck.

The pole carrier is free to pivot in the horizontal plane, and the collector head is pivoted in the same plane. The collector head has a groove which sits around the contact wire. This means that the collector will follow the wire as the vehicle moves along the track, with the trolley pole slewing right or left as necessary.

Modern trolley poles are double insulated (section 10.10.2) with one insulating layer below the collector head, and the second at the pole base.

Figure 275: Trolley pole on single deck tram. Beamish, UK

Trolley poles on trolley buses are usually longer than those on trams, to provide the driver with more freedom to deviate away from the OLE, allowing them to pick up and drop off passengers at the kerbside[167].

[165] The trolley pole was invented in 1885 by Charles Van Depoele. en.wikipedia.org/wiki/Charles_Joseph_Van_Depoele.

[166] Historically, wood and steel were also used.

[167] Videos taken from pole-mounted cameras on trolleybus systems provide an excellent overview of the system at work; see videos at youtu.be/QHxMKWCm1dM and youtu.be/MhCtfE08pP4 for examples.

Figure 276: Trolley poles slewed for kerbside drop-off and boarding. Vancouver, Canada

The collector head originally came in two distinct forms. The *wheel collector* used a freely rotating wheel that pressed on the contact wire. This had the advantage that no carbon needed replacing, but the small metal-to-metal contact patch between the wire and wheel led to increased arcing and wear. This system is seldom used now and is only found on heritage and museum trams.

Figure 277: Wheel collector

Instead the *slipper collector* is now standard; this uses a carbon block that sits within a grooved carrier which can pivot in the vertical plane (a *fixed slipper collector*). More recent designs also swivel in the horizontal plane (a *swivel slipper collector*); this double articulation minimises the chance of dewirement. The carbon block is replaced when worn, in the same way as the carbon strip on a pantograph. The slipper collector provides quieter operation and less sparking than the wheel type[168], but both types were popular in pre-war tram systems.

Figure 278: BICC swivel slipper collector head

Crucially, the trolley pole system only works when the collector head is behind the vehicle in the direction of travel, as it relies on the restoring force of the vehicle's motion, which is always trying to return the trolley pole to its neutral axis. Attempts to drive the vehicle in the opposite direction (at anything other than very low speeds) will result in the pole leaving the wire.

Vehicles using this system therefore cannot reverse direction until the trolley pole has been rotated

[168] "Electric Traction", A.T. Dover; Third Edition, 1929; Pitman; p211.

through 180°. This was originally undertaken manually by a person using an insulated pole[169], but this time-consuming process does not lend itself to short turnback times, and requires the driver to place themselves at risk in busy traffic. In the UK the *reversing triangle* became popular in the OLE design; this uses the natural resistance of the trolley pole to being pushed rather than pulled, to effect an automatic reversal using spring-back frogs (section 14.4)[170]. To avoid the need for this operation, many trams were fitted with a trolley pole at each end of the vehicle, with a manual changeover process at each end of a route. Modern trolleybus systems utilise a simple turning circle at each end of the route, so that vehicles do not need to reverse direction.

The propensity of trolley poles to accidentally leave the wire means that a system of restraint is needed to prevent damage to the OLE. An insulated rope is often provided between the vehicle roof and the top of the pole, and fitted with a manual raise/lower mechanism to assist the operator. The function of this mechanism is often extended to become a *trolley retriever*; this prevents the pole rising rapidly in the event of coming off the wire.

Figure 279: Trolley Retriever. Ottawa, Canada

Many modern trolley poles use a pneumatic actuator, and this offers an ADD functionality similar to those in pantographs (section 11.1) by detecting a dewirement event, and rapidly dropping the trolley pole by exhausting the air circuit. Systems using pneumatic trolley poles can also be fitted with *threading horns* mounted on the OLE at specific locations, allowing the raising of the pole and locating of the collector head to be carried out without the driver leaving the cab.

14.2. Trolley Support Systems

Early trolley systems used a contact wire (section 11.16.1) of circular section without notches, with fittings clamping around the top half of the section[171], but this form of clamp was necessarily wider and necessitated the use of wheel collectors to maintain adequate current collection. As the advantages of slipper collectors became clear, a means of narrowing the profile of the contact wire support fixing was needed, since a conventional contact wire swivel clip (section 11.16.1) would be too wide and foul the slipper as it passed through. Trolley

[169] A video of manual reversal can be seen at youtu.be/yfKCsQQ-SZA.

[170] A video of a reversing triangle in operation can be seen at youtu.be/1maKZSOb1HU.

[171] "Current Collection for Tramway & Trolleybus Systems", Baddeley, Oakley; 1975; p9.

systems therefore use a slimmer, longer assembly, to achieve the same clamping force without fouling the collector. This clamp is known as an *ear*.

On many systems ears are attached to a *hanger* which provides the same horizonal pivot function as swivel clips on conventional OLE. An insulator connects the hanger to the ear, providing a single level of insulation, and is typically supplemented by insulators in the span wire to form double insulation (section 10.10.2) and to maintain electrical separation between tracks.

In the UK the *twin line hanger* was the standard fixing for trolleybus systems, consisting of two ears separated by a rigid insulator; whereas North American systems favoured separate ears.

Figure 280: Straight hanger and ear. Beamish, UK

Hangers are adequate for slow speeds, but as speed increases – as with modern trolleybus systems – the hard spot (section 11.1.2) formed by the traditional hanger increases arcing and wear. They are also incompatible with pantograph working. Modern systems often use either conventional bridle tramway OLE (section 11.2) or a *pendular support* system, which uses a pair of flexible wire hangers and parallelogram fittings to maintain the verticality of the wire, regardless of radial load.

Figure 281: Pendular trolley supports. Vancouver, Canada

Tram systems typically have more curves of smaller radii than conventional railways as they negotiate narrow city streets, and so frequent use is made of flying tails (section 11.10.5), either to buildings or poles via *span wires*. Also known as *pull-offs*, these would twist the contact wire if directly connected, and so hangers are divided into the *straight* type, only for use on tangent track, and the pull-off type for use on curves. Pull-off hangers are arranged such that the radial load from the pull-off intersects the centre of the contact wire, keeping it level. Ears on these hangers are also curved, to avoid the high stresses that would otherwise occur in the contact wire at the point of radial load.

Figure 282: Spanwire pull-offs. Beamish, UK

On tangent sections of track, support may either be by span wires, or if road width and aesthetic restrictions permit, by using cantilevers (which on tram and trolley systems are referred to as *bracket arms*). Where these are used, they are typically designed to be aesthetically sympathetic to their surroundings. Early tram systems were driven by the need to reduce steelwork costs[172], so back to back bracket arms or twin track poles were favoured.

Figure 283: Pull-off hanger. Beamish, UK

Figure 284: (l-r) spanwire support, back to back bracket arm support. Beamish, UK

[172] An additional factor was that local authorities would often charge the tram company a levy for each pole installed. Ibid.; p12.

Figure 285: Twin track pole. Ottawa, Canada

Tram and trolley systems at curves and junctions employ much more sophisticated span wire connections than conventional OLE to achieve the required contact wire position; multiple span wires may be anchored at a single point, and wire runs may have pull-offs connecting them together, providing the same function as knuckles (section 11.13.2) in conventional OLE. Tensions are lower than for mainline systems and this helps to reduce radial loads (section 11.14). The wiring arrangement for a complex junction can however weigh more than one tonne.

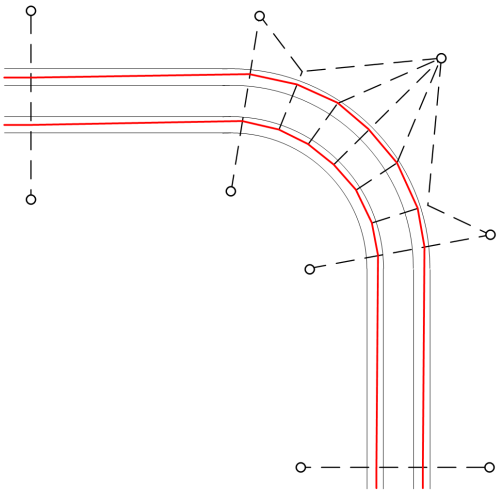


Figure 286: Trolley wire geometry on curves

It is not necessary to adopt staggering rules as with conventional OLE (section 11.13.2), but that does not mean there are no limitations on the lateral position of the wire. The natural path of the trolley pole must be considered, and this forms the basis for the design of the wiring geometry, particularly on curves.

Trolley masts are often circular hollow section, providing the necessary strength as well as a degree of aesthetic harmony with a high street environment; this also provides a convenient protected conduit for feeder cables. However these have the disadvantage that their inner surface is hidden and so corrosion is much harder to detect. It is therefore essential that hollow masts are capped at the top to prevent rainwater incursion.

14.3. Insulators for Trolley Systems

A variety of different insulator types may be found in trolley systems. *Loop insulators* are popular for insulation within spanwires, as are *globe-and-link insulators*.

Figure 287: (l-r) porcelain loop insulator, globe-and-link insulator, composite loop insulator

Trolley systems require section insulators (section 11.6.1) for the same reasons as conventional OLE systems. However the need to guide the collector head means that the contact wire insulator must present a shape that matches the contact wire.

This led to the development of a standard SI for trolley systems which comprises a running insulator made of a hard-wearing plastic[173] (which is reversible to double its life span) clamped between cast contact wire termination fittings. Two rod insulators sit above the runner and provide the assembly with the necessary stiffness, as well as a useful clamping location for support assemblies. This SI forms the core of a modular fittings system for junctions, with feeder and jumper terminations built in, and direct connections to frog and crossing units (section 14.4).

Figure 288: BICC trolley section insulator with support clamp and feeder terminations. Beamish, UK

14.4. Arrangements at Turnouts

Special arrangements are needed where wire runs diverge and converge, since unlike pantograph operation, the collector head must be actively or passively guided onto the correct wire. Unlike conventional OLE, the low tensions and speeds mean that it is practical to split one wire run into two; this is done using an assembly known as a *turnout frog*, mirroring the terminology used in the track discipline.

Three distinct types of frog are available, and the selection of the right type depends on the track turnout type and mode of operation.

The simplest type is the *fixed frog*, which comprises a grooved casting offering a path for the collector head in both directions. These can use used in both trailing and facing turnout configurations. When used in a trailing arrangement, the collector head will naturally take the correct path through the frog. However when used in the facing configuration, the orientation of the collector head will determine the path it takes, and this means that it can only be used with fixed collector heads (section 14.1).

[173] Early insulators were made of hardwood and then Bakelite. Ibid.; p18.

The second type is the *spring-back frog*. Here the fixed casting provides the path into the frog, but the central section contains a pivoted *tongue*. This tongue is spring-loaded to normally lie in one direction. This is then installed over a track turnout which is also spring-loaded to lie in the same direction.

Collector heads approaching in the trailing direction will naturally take the right path, those coming from the non-favoured direction pushing the tongue into the correct orientation; the tongue will return to its default path as the collector head clears the tongue. This is mirrored in the behaviour of the vehicle, the wheels providing the force to move the switch rails. Collector heads approaching in the facing direction will always take the default path, as will the vehicle itself.

Figure 289: Spring-back frog. Beamish, UK

For turnouts where trams can take either route in the facing direction, active measures must be taken to switch the tongue to the correct route before a trolley pole passes, and so a *switched frog* will be used. This has the same components as the spring-back frog, but a lever actuator is provided so that the tongue can be switched to either orientation.

Figure 290: Switched frog. Beamish, UK

The means of providing this actuation varies depending on the age and sophistication of the system. The earliest and simplest arrangement was to provide a manual operating handle at ground level, which would be switched by a member of staff before each tram passed. A spring-back frog was generally used, allowing a simple cable actuator to be used rather than a push-pull linkage. In some cases the switching of the track and OLE was effected by means of one operation.

This time-consuming process is not suitable for the modern era, so automatic switching of the OLE frog is provided, using the orientation of the vehicle. There are a number of ways to achieve this.

Early systems used the vehicle orientation; in this arrangement a switched frog is located beyond the turnout, so that by the time the collector head reaches the frog, the vehicle is beyond the track turnout and already well along its chosen route. The tongue is actuated by a long lever at the frog, that hangs well below contact wire level in such a way that when the lever is vertical, the tongue is set for straight on.

When the track turnout is set to route the vehicle in the straight direction, the trolley pole will pass the lever without engaging it and the frog remains set for straight on. When the track turnout is set in the diverging direction, the vehicle passes through and the pole naturally moves away from the track centreline. As the head approaches the frog the pole engages and lifts the lever, temporarily moving the tongue to the diverging route.

The lever length is set so that the head is safely through the frog before the lever is released, the tongue returning to the straight through orientation[174].

Modern systems provide full automatic operation of both track and OLE turnouts, with the driver selecting the appropriate route. This is used in both tram and trolleybus systems, and can be achieved in a number of ways[175].

The *power-coast* system uses the traction current flow itself to actuate the OLE frog (and for trams, also the track turnout) through a relay system. If the driver is not taking power, the switch will not actuate and the collector head will continue straight on. If the driver is taking power, the OLE and track turnouts are actuated and the vehicle will take the diverging route. This system relies on the appropriate use of the driver's power handle, which can be a challenge at some locations where either coasting or drawing power is not operationally appropriate.

The *Selectric* system works in a similar way to the mechanical lever system, but uses the orientation of the collector head as it approaches the frog to determine which route is being taken. A head taking a straight-through route will bypass the electrical contacts, whereas one taking the diverging route closes the contacts and actuates the frog. Selectric can be used in trolleybus systems, where contacts in the positive and negative wire are positioned so that only poles taking the diverging route will simultaneously make contact and switch the frog.

The *Fahslabend* system achieves full automation by linking a radio system in each vehicle to the driver's turn indicator. Thus the whole route can be set by the driver's explicit intention, without the need to take power or coast.

For all these systems, a mechanical switch can be placed on the wire beyond the frog, triggered by the collector head to reset the switch; whereas other systems use a simple time-delay reset to achieve the same functionality.

14.5. Arrangements at Crossings

Where two wires cross and are of the same electrical section on a tram system, a simple grooved diamond is provided which mirrors the function of a track diamond.

Figure 291: Diamond crossing. Beamish, UK

Trolley bus systems bring additional challenges when wires cross, since the positive conductor must cross the negative one while remaining electrically separate, and vice versa. Therefore the crossing must incorporate insulation, using two section insulators (section 11.6.1) either side of the crossing in one of the wire runs; and a jumper across the diamond to maintain electrical continuity.

[174] A video of this operation can be found at youtu.be/2hJQEewcbhQ.

[175] en.wikipedia.org/wiki/Trolleybus#Wire_switches.

Figure 292: Wire crossing section insulators and jumper. Beamish, UK

14.6. Disadvantages of the Trolley System for Trams

As can be seen, the trolley system, being a guided collector, requires all of the switch and crossing features that guided railway track systems do. The complexity of providing all of these in an aerially suspended system adds construction and maintenance cost, and means that it is not uncommon for trolley poles to lose contact with the wire when travelling on these systems[176].

Figure 293: Skid assembly at frog for trolley-pantograph mixed working

[176] A video of a trolley pole dewirement can be seen at youtu.be/OfSDu-Vbh4E.

For this reason modern tram systems are specified with conventional OLE and unguided pantographs, and many older systems have been converted to pantograph operation. This creates a dilemma for existing trolley system owners, since it is very disruptive and expensive to convert a whole system and fleet at once. Arrangements have therefore been developed to allow mixed working of collector heads and pantographs, typically using a skid at switch and crossing points to depress the pantograph a little as it passes through the junction. However some systems, such as Lisbon, choose mixed working on a single vehicle as a permanent arrangement, taking advantage of the narrow swept envelope of the trolley pole in areas of narrow winding streets, and using the more reliable pantograph working elsewhere.

15. Special Arrangements

The arrangements described so far in this book are for conventional overhead contact systems. However a number of non-standard configurations can be found at locations around the world; these came into being either through historical quirks, technological dead-ends, or as a response to the special conditions within which the system must operate.

15.1. 50kV Supply Voltage

A handful of mining railways have operated with a supply voltage (section 10.1) of 50kV. The higher voltage provides the ability to power heavy mining trains for long distances with fewer feeder stations. Of these, only the Sishen–Saldanha railway in South Africa remains operational.

Figure 294: 50kV OLE on a mining railway - note the unusually long insulators. Sishen–Saldanha, South Africa

15.2. Three Phase OLE

The supply of a single phase OLE system from a three phase grid causes additional complexity (section 10.1.3). A handful of railways have tried to implement three phase AC overhead line – some successfully, others less so. A three phase OLE system allows for easy regeneration of kinetic energy under braking back into the three phase grid, and this made it an attractive option for mountain railways. However any such advantages are more than offset by the complexity of providing two electrically separate contact wires – the traction return rail providing the third phase – and the use of squirrel cage AC motors, which only operate at a single rotor speed. There are now only four such railways operating in the world[177].

[177] More information is available online at en.wikipedia.org/wiki/Three-phase_AC_railway_electrification.

Figure 295: Three phase AC mountain rack railway; note the dual contact wires and bow type current collectors. Petit train de la Rhune, France

15.3. Dual Voltage Crossings

There are occasionally locations where two railways of differing voltages cross at grade. The most well-known of these is in Melbourne, Australia[178], where the 600V DC tram system crosses the 1500V DC mainline system. At these locations a special OLE subsection is created, which is isolated from high and low voltage sections on either side, but capable of being fed at either voltage. The supply switching is interlocked with the signalling system, meaning the correct voltage is supplied for the tram or train due to cross.

[178] More information is available online at en.wikipedia.org/wiki/Trams_in_Melbourne#Tram.E2.80.93train_level_crossings.

Figure 296: 1500V DC train meets 600V DC tram. Kooyong, Melbourne

15.4. Inclined OLE

The main constraint on span length between structures – and therefore OLE cost – is the deviation of the straight contact wire from the track centreline at midspan (section 11.13.2). The purpose of inclined OLE is to force the contact wire to more closely follow the curve of the track. By doing this span lengths can be increased, with a corresponding decrease in support steelwork costs.

The horizontal curvature of the contact wire is produced by offsetting the catenary wire (section 11.16.3) to a significant degree towards the outside of the curve. This forces each dropper (section 11.16.4) to become inclined, imparting a radial load on the contact wire which pulls it outwards and reduces the midspan offset. Each dropper effectively becomes a registration point, with the contact wire striking a series of chords between droppers rather than between structures. Depending on the extent of the inclination, this configuration can also remove the need for registration arms (section 11.13.2) altogether.

Figure 297: Inclined OLE - note the absence of registration arms. Philadelphia, US

Inclined OLE is especially useful on routes with many small radius curves, such as those in the Swiss mountains. The system requires careful design, construction and maintenance to ensure that the vertical and horizontal force components are balanced; and also requires inclined dropper clips (section 11.5.7) to prevent the radial loads from twisting the dropper clips over into the path of the pantograph carbons (section 11.1).

15.5. Moving OLE

There are a number of scenarios where is it necessary to provide OLE that is capable of being moved. This requires special arrangements, both mechanically and electrically.

A common scenario is in maintenance depots, where for shunting convenience OLE is generally provided into the inspection and maintenance sheds, but where this OLE then poses a safety hazard and prevents access to the roof on the train. Modern rolling stock often maximises passenger capacity by moving air conditioning and other equipment into the roof space, meaning maintenance access is necessary.

The standard solution is therefore to provide a ROCL system (section 11.16.2) on supports which can swing horizontally through 90°, or lift vertically, retracting the OLE away from the train and allowing access. This system is electrically interlocked with the depot power supply and staff warning systems, so that the OLE cannot be retracted until it is isolated and earthed, and staff will not receive permission to access the roof until that process is complete[179].

Figure 298: Retractable rigid overhead contact line. Temple Mills, UK

[179] Video of a retractable depot conductor bar in operation is available online at youtu.be/lM5hYT-Xs3s.

A much more technically demanding problem exists where a railway crosses a navigation channel by means of a lifting (or *Bascule*) bridge or a swing bridge. It is usually not practical to raise the level of the bridge to make it fixed, since shipping has guaranteed access upriver. In this case it is necessary to build an OLE arrangement which can swing or raise/lower with the bridge. As with depot systems, ROCL is an ideal solution[180].

Unlike depot OLE, these systems often need to operate at significant speed, and the transfer mechanism from fixed OLE to moving must be carefully designed to ensure that alignment and elasticity change is carefully managed. Additional complications arise from way the bridges move; for bascule bridges, the counterweight swings downward to occupy the space immediately above track level. This means that a section of the rigid bar must be retracted out of the way prior to the bridge lifting to make way for the counterweight. Sophisticated designs have been developed to achieve this, using winch-actuated portal structures running on rails to pull the ROCL away from the bridge, with special sliding electrical connectors to ensure electrical continuity onto the bridge. The portion of ROCL on the bridge is within touching distance of track level when the bridge is raised, so motorised isolators (section 11.7) are provided to connect the ROCL to earth. All of these arrangements must be mechanically and interlocked with both the bridge actuation and the railway signalling system. Traction power continuity must be provided across the bridge even when it is raised, so submarine traction feed cables are provided across the navigation channel.

Swing bridges have similar movement challenges and solutions; a rotary rigid bar overlap section is provided at each end of the bridge, which rotates in the vertical plane to provide a clear space for the bridge ends to move through.

Figure 299: Bascule bridge with overhead conductor bar. Peenebrücke, Germany

Some electric freight railways have a requirement to load hopper wagons from above, and so it is necessary to have a break in the OLE. This can be achieved by having anchor portals either side of the hopper feed, with skid arrangements in the contact wire to manage the pantograph as it leaves and re-joins the OLE at slow speed.

[180] "Electrification of Swing and Bascule Bridges with Overhead Conductor Rails", Cox, Nünlist, Marti; September 2000; Furrer+Frey.

15.6. Roundhouse OLE

Historically many railways used the *roundhouse* concept - a circular or semi-circular locomotive maintenance shed surrounding a turntable. As electric traction was introduced, some of these were electrified, and a few still survive today. The OLE configuration comprises a central ring positioned over the turntable centre, which acts as the termination for a series of radially-arranged contact wires; each contact wire services one shed road, and the balance of tensions holds the ring in place.

Figure 300: Electrified Roundhouse. Landquart, Graubünden, Switzerland

The roundhouse shown above is arranged with two through-running contact wires, which cross at 90° to each other, so that pantographs are able to pass through the very centre of the turntable without snagging.

15.7. Offset OLE

Some railways use an OLE system which is offset from the track centreline, in order to deal with a specific constraint on the route. For instance, in Zurich the *Sihltalbahn* railway is electrified with 15kV AC OLE, while the *Uetlibergbahn* railway uses 1200V DC OLE. The two systems share a single set of tracks for part of the route; on this section the DC OLE is offset to the side, and DC trains have their pantograph offset to the same extent. AC trains are provided with a pantograph on the train centreline as normal.

Figure 301: (l-r) 1200V DC EMU with offset pantograph on the Uetliberg railway, 15kV AC (left) and 1200V DC (right) ROCL on the shared section. Zurich, Switzerland

15.8. Electric-Steam Traction

Shortage of coal during World War 2 drove Swiss Federal Railways to fit two coal-fired steam locomotives with pantographs, hydro-electric power being plentiful in the region.

Figure 302: Electric-steam loco in Switzerland in 1942

The locos used traction current from the 15kV 16.6Hz OLE to boil water using an electric heating element, creating steam pressure to move the locomotive. Pressure was sufficient to run off the wires for around 20 minutes before returning to recharge.

16. Interfaces with Other Systems

OLE interfaces with almost every other railway system, and several non-railway systems. It is often at the interfaces that unexpected failures can occur; for this reason it is vital the these are fully considered in the design process (section 18). The key interface issues to be considered during OLE design are discussed below.

16.1. Permanent Way

This is the one of the most important interfaces, since the OLE must follow the track geometry. Particular items to understand are:

- Track position;
- Track tolerances (which must be allowed for when designing OLE, particularly through overbridges) and any managed track position strategy (section 17.8);
- Track lift, slew and change of cant (for projects with an element of track modification);
- Available extent of track lowers (for bridges with insufficient clearances);
- Position of toes of points;
- Areas of reduced track stability (when constructing adjacent foundations, particularly in hot weather when rails may be beyond their *stressing temperature* and prone to buckling).

16.2. Geotechnical

This is also a key interface, since it determines the long-term stability of the OLE. Particular items to understand are:

- Natural ground types (in cuttings and flat ground);
- Made ground types (on embankments);
- Slope stability;
- Mining areas and subsidence risk;
- Grouting, toe loading and other slope remediations.

This is discussed further in section 18.1.3.

16.3. Civil & Structural

Key civil and structural issues to be considered are:

- Electrical clearances to overline structures;
- Attachment to structures.

16.3.1. Bridge Fixings

Fixings to overbridges include supports for bridge arms (section 11.10.9), conductive assemblies (section 10.10.1) and earth wires. The type of fixing used depends on the form of construction of the bridge, the location of the fixing on the bridge, and the loads imposed on it.

Access to these locations is often highly constrained, and so preference is given to fixings which can be rapidly installed without drilling. Where the bridge is of metallic construction, fixing designs based on *Lindapter clamps* are frequently used to clamp to an L-, H- or C-section bridge member. These clamps come in a range of different types, to suit different clamping requirements. A key advantage of these clamps is that they provide positional flexibility; for instance, when combined with a new C-channel beam they can provide cross-track

adjustment for bridge arms.

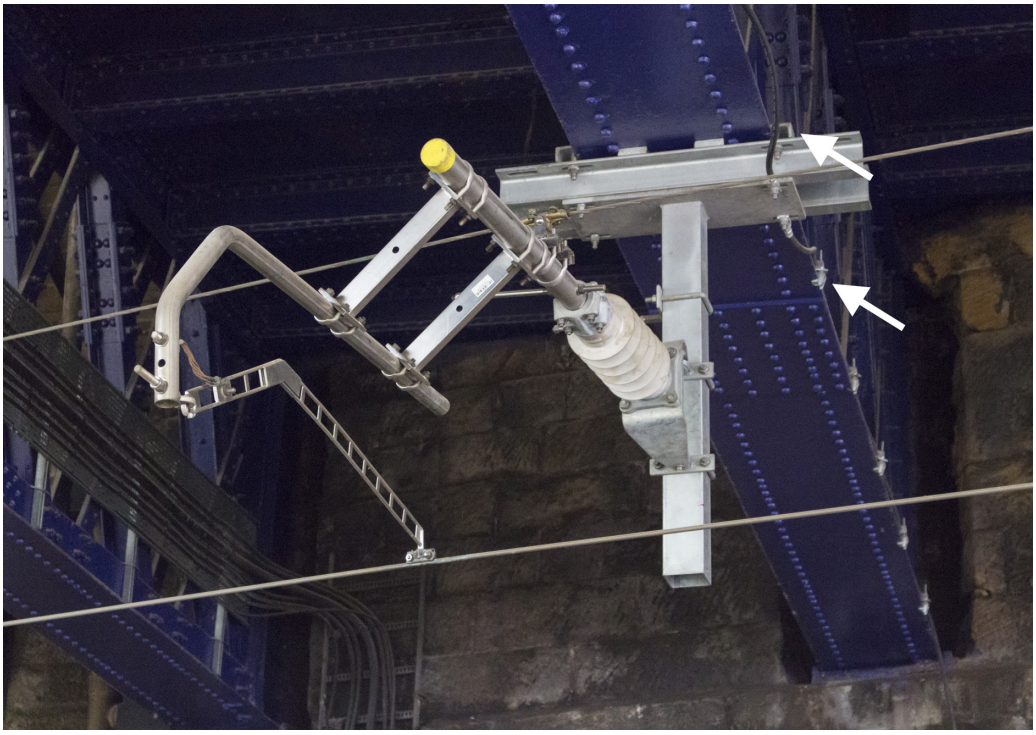


Figure 303: Different styles Lindapter clamps (arrowed) used for bridge arm support and bonding cable support to steel bridge girder. Glasgow, UK

Lindapter clamping is not suitable for concrete bridges, which pose additional challenges since they are often pre- or post-stressed, containing *reinforcing bar* (or *rebar*) which cannot be drilled into without compromising the structural integrity of the bridge. Some concrete bridges are constructed with I-section parallel prestressed decks beams with narrow gaps between them; these offer the opportunity to use a steel *T-bolt* which comprises a thread bar welded to a T-shaped paddle to match the slope of the beams. The bolt is inserted into the gap between the beams and rotated through 90°. The assembly to be supported is then clamped to the bolt, which exerts force on the back of the beams.

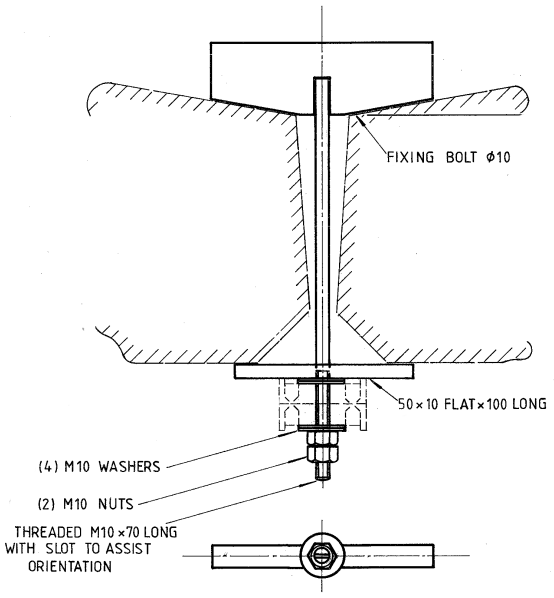


Figure 304: T-bolt design for prestressed concrete beam fixings[181]

For concrete and brick structures where drilling cannot be avoided, *chemical resin anchors* are used. These take the form of a threaded bar (usually of stainless steel) which is secured in a pre-drilled hole in the masonry using a rapid-curing resin injection mortar. The anchor product to be used must be carefully selected to meet the loading, performance and environmental criteria, as well as the brickwork type and condition.

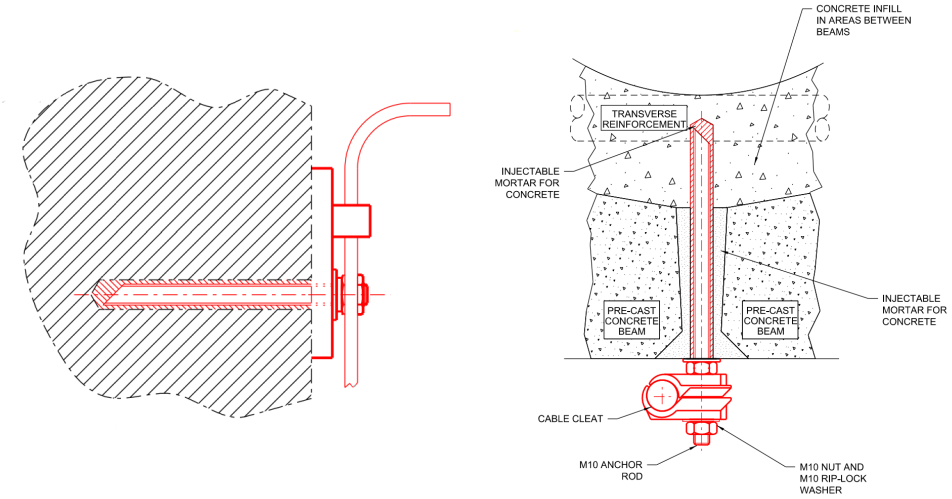


Figure 305: (l-r) Resin anchor bolt designs for earth strip support on a concrete bridge abutment, earth wire support from infilled concrete beam bridge deck

16.4. Modern Tunnels

Tunnels present unique spatial and environmental constraints for OLE, and the design, construction and maintenance of OLE in tunnels must take account of these. The nature of these constraints varies widely depending on the age of the tunnel, its form of construction and the geology through which it travels.

Modern tunnels are usually constructed using *Tunnel Boring Machines* (TBMs), which cut a circular bore or bores (two track railways often being formed of two single bores). Each bore is then lined with concrete segments to form a watertight[182] cylindrical bore. Constructing tunnels in this way is a costly, complex and time-consuming process, and the diameter is usually minimised to avoid further expense. This means that the space available for OLE between the train and the tunnel is often both small and unusually shaped, and this often precludes the use of conventional OLE, which requires space-consuming cantilevers to provide the necessary along-track movement (section 11.3). The shape of the tunnel often means that lateral space is as much of a constraint as vertical space.

Conventional OLE with bridge arms (section 11.10.9) is not generally used in long tunnels, due to the potential for mechanical resonance (section 11.13.1) as the pantograph passes through the regularly-spaced short spans, causing excessive wear and loosening of fittings. Bridge arms can be used for shorter tunnels, but care is needed in design and construction, since the short spans require tighter tolerances to avoid uneven contact wire gradients.

[181] OLEMI Drawing 1/076/852/A3 "Assembly of 10ϕ Fixing Bolt Used with Cable Cleat on Pre-stressed Concrete Beam Decks"; revision 0; British Railways Board; 1984.

[182] Some leakage can be expected over the life of the tunnel, and so drainage measures are also included in the tunnel design.

Figure 306: Conventional 300mm system height 1500V DC OLE in a Victorian tunnel (right) in the process of being converted to sliding ROCL (left) as part of a gauge increase project; the space advantage of ROCL can clearly be seen. Sicily, Italy

For this reason, electrification of small-diameter modern tunnels is often undertaken using ROCL (section 11.16.2); while this does not have any construction depth advantage over twin contact OLE[183], it occupies significantly less space - both vertically and horizontally - than conventional small system height OLE. This is possible because ROCL overlaps are very simple compared to those in conventional OLE (section 11.4.2), and so can be frequently installed, reducing along track movement. The remaining movement can be accommodated using either a short pivoting support, or a sliding ROCL support, removing the need for pivoting cantilevers altogether and reducing the size of the supports even further.

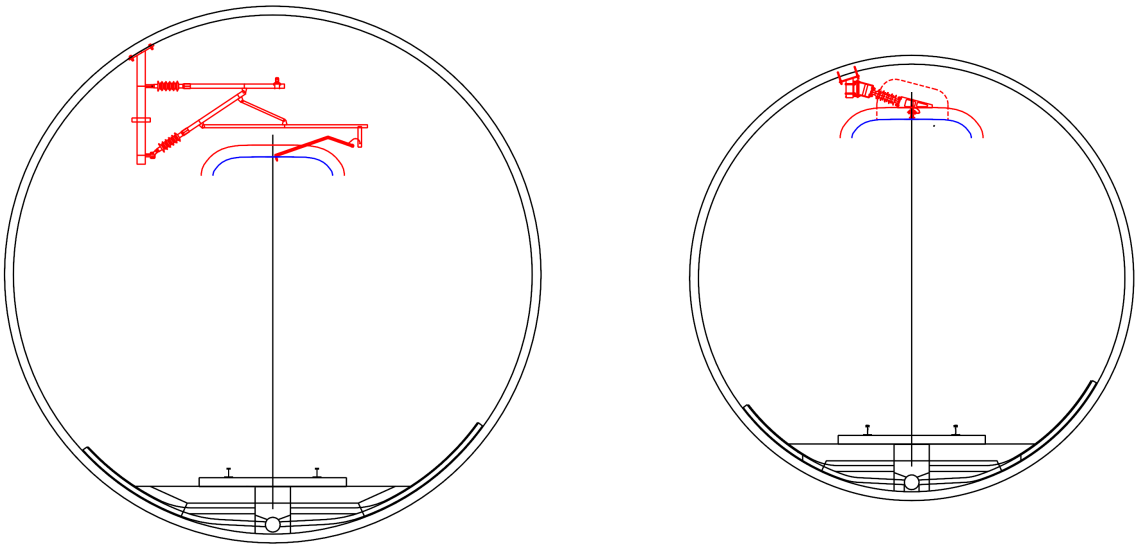


Figure 307: (l-r) OLE systems in modern circular section tunnels; large diameter single bore with conventional OLE, small diameter single track bore with ROCL

ROCL has another major advantage over conventional OLE in a tunnel – it is much more resistant to fire or

[183] Twin contact conventional OLE has a live construction depth of around 120mm plus 70mm allowance for uplift, whereas ROCL construction depth is typically around 200mm (110mm for the bar, and the remainder for the live support bracket), but does not experience any significant uplift.

electrical flashover damage, and in dewirement scenarios will not release mechanical energy in the way that a tensioned system would. This is essential given the stringent safety requirements in modern tunnels.

Some modern tunnels have a larger diameter, and these use conventional OLE, which is significantly cheaper than ROCL[184]. Regardless of age, tunnels have a much narrower operating temperature range than an outdoors environment, and so it is possible to use a longer tension length matched to those conditions. However if the tunnel is longer than the resulting maximum tension length (section 11.3) then tensioners must be provided within the tunnel, and this is typically achieved using specially-configured weight stacks (section 11.10.10) designed to sit on the flank of the tunnel wall, or if space is particularly constrained, in pockets set into the tunnel wall. The short span lengths typical of tunnels, combined with the lack of cross-track wind, means that blowoff (section 11.13.2) can safely be ignored. Along-track windspeeds are high, as a result of the piston effect of passing trains[185].

Regardless of the type of OLE used, the supports are usually fixed into the cast concrete segments using resin anchors (section 16.3.1), although mechanical rawlbolts are sometimes used, or recesses can be precast into the segments to receive T-bolts.

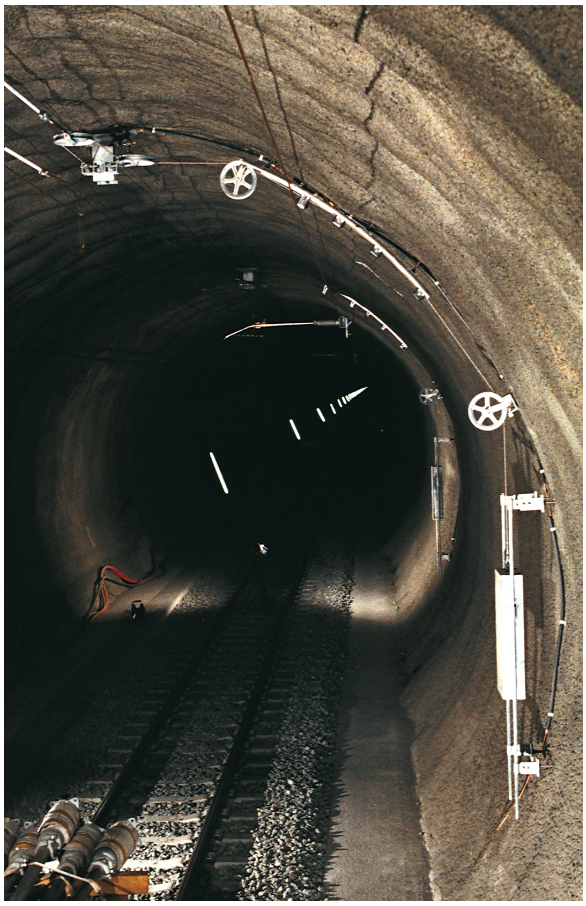


Figure 308: Tensioning pulleys and balance weight stack in a tunnel. Vereina, Switzerland

16.5. Historic Tunnels

Older tunnels present a number of different challenges. Unlike modern tunnels, the shape, construction and condition of older tunnels varies widely depending on a variety of factors. It is essential to understand the history of the tunnel before design work can begin.

16.5.1. Tunnel Configuration

The basic configurations of historic tunnels in the UK are as follows:

- Tunnels in stable rock conditions are usually unlined; there are currently around 30 unlined tunnels in the UK - an example can be seen at Ffestiniog;
- Tunnels in rock of a less competent nature typically have a relatively thin cosmetic lining to prevent rock falls onto the track; this often takes the form of vertical side walls of stone masonry, a brick semi-circular arch around 450mm thick, and no invert. An example can be seen at Clifton Down Tunnel;
- Tunnels in even softer rock, or softer ground such as clay, typically have a horseshoe profile made up of five circular curves, and no invert. Somewhere around 600 of the 750 currently operational UK tunnels are of this type - an example can be seen at Standedge Tunnel;

[184] Video of conventional OLE installation in a modern tunnel is available online at youtu.be/BGbOH7T7MUg.

[185] A windspeed equal to twice the linespeed is sometimes used in structural calculations.

- Tunnels in even softer ground such as clay, sands or gravel typically have a horseshoe profile made up of five circular curves, with a *structural invert*[186] - examples can be seen at Bletchingley and Saltwood Tunnels;
- A few tunnels in over-consolidated clay (such as London Clay) experience very high horizontal forces, and these have a circular or near-circular profile to resist the ground load - an example can be seen at Hadley Wood;
- A few tunnels have an elliptical profile with a horizontal major axis to resist large horizontal forces - an example can be seen at Toadmoor Tunnel, which was built through a landslip area.

Figure 309: (clockwise from top left) Clifton Down Tunnel, Standedge Tunnel, Hadley Wood North West Tunnel, Toadmoor Tunnel

[186] An upside-down arch under the track which resists horizontal forces from the surrounding ground.

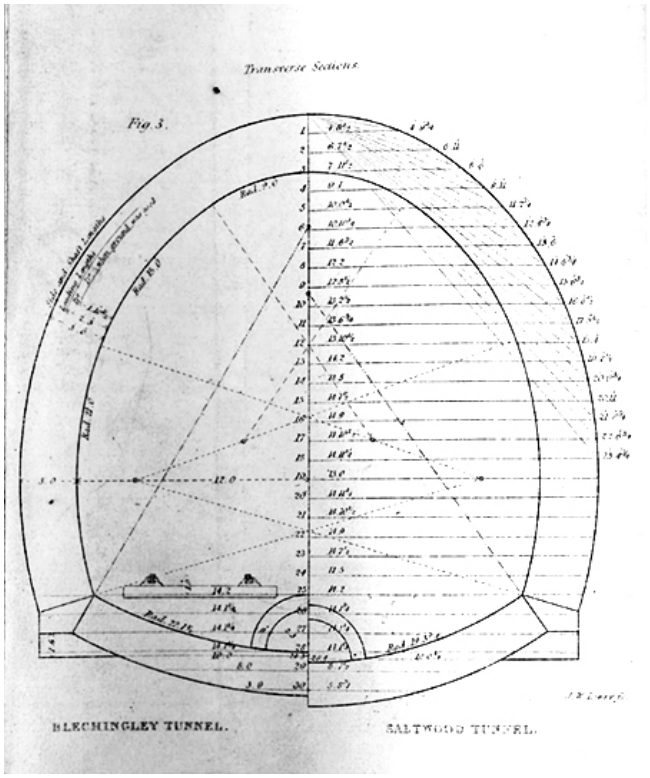


Figure 310: Profiles of Bletchingly (left) and Saltwood (right) Tunnels, showing invert

16.5.2. Construction Techniques

Short tunnels (up to about 300m long) were usually built inward from the two ends, after driving a small *heading* from one end of the tunnel to the other to establish the alignment. Longer tunnels were more commonly driven outwards as well as inwards, using one or more *vertical shafts* driven down from above, permitting multiple *working faces* to be established to speed up construction[187]. While some construction shafts remain open today for ventilation, some had no use beyond the construction stage and so were bricked over at the bottom end and infilled from above, resulting in *blind* or *hidden shafts*. Where the tunnel lining meets these shafts there can be some misalignment due to original survey errors, but this is relatively rare. Many twin track historic tunnels in the UK are around 7.5m wide and 6.1m high, but dimensions vary considerably due to the requirements of the multitude of original railway companies. It is also relatively common for the tunnel profile to change within the length of the tunnel - for example, having a horseshoe profile for part of its length and semi-circular arch on vertical side walls for another.

Figure 311: Witch's hat cone and support frame at an open vent shaft. Sevenoaks, UK

Longer tunnels were provided with permanent vent shafts at fairly regular intervals to permit steam to escape, and these offer further routes for water ingress during rainy conditions. These are sometimes fitted with a

[187] For more information on the construction techniques used in historic tunnels, see Graeme Bickerdike's "Tunnel Vision" video at youtu.be/_c8jvixQGpQ.

witch's hat, an inverted cone that deflects water coming down the shaft into a *garland gutter* around the shaft perimeter, while permitting air to flow up or down the shaft in response to pressure from passing trains.

16.5.3. Water Ingress

Some tunnels pass through impermeable geology, and will remain dry; whereas tunnels through permeable rock will experience frequent groundwater ingress at multiple points, typically forcing its way through gaps in the mortar. Some may even have underground springs emptying into them. The Severn and Abbotscliffe Tunnels are examples of this.

Figure 312: Examples of water ingress in a wet tunnel. Severn Tunnel, UK

Wet tunnels are often provided with a system of weep holes and drains, to allow water to enter the tunnel without damaging brickwork, and to manage flow out of the tunnel. In some cases water ingress is captured by drainage pans fixed to the lining, drip shield sheeting or decking (Balcombe Tunnel is an example with drainage decking) and these can be significant challenges for electrification. In extreme cases mineral-rich groundwater can form stalactites, which can build up on OLE components, fouling mechanisms and reducing air gap clearances (section 10.8).

16.5.4. Tunnel Masonry

The quality of brickwork in a tunnel *crown* and *haunches* varies considerably, even between tunnels built by the same contractor on the same route. The compressive strength of the bricks increased from the 1830s to the 1860s, as they were often made in the adjoining cuttings using portable kilns, the effectiveness of which improved over time; resulting brick strengths can be as low as 13N/mm^2 and as high as 50N/mm^2. The mortar was commonly a sand and lime mortar mix, with a typical strength of 1-2N/mm^2, but occasionally the mortar is described as *cement mortar* and this can be stronger - perhaps 2-4N/mm^2. Occasionally drawings will refer to *roman cement*, a rapid hardening waterproof material developed in the early 1800s and used when conditions were very wet, such as in the Brunel's Thames Tunnel. With a reddish brown colour similar to roman terracotta materials, this can have a strength of 3-10N/mm^2.

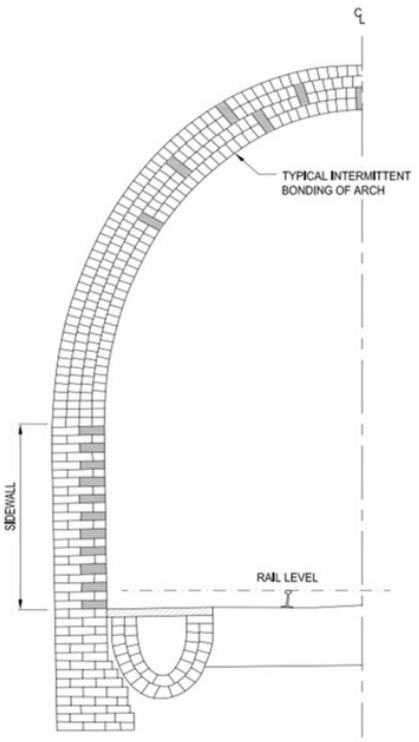


Figure 313: Individual arch rings with intermittent bonding at Standedge South Tunnel

Most early tunnels were built with the haunches and crown in a series of separate unbonded rings of bricks each about 110mm thick; these only align intermittently due to the increasing number of bricks in each successive ring. Later in the 19th century some tunnels were built with two 225mm bonded brick rings. Regardless of the construction detail, the brick rings were formed over temporary timber formwork, and this often led to the outermost rings (which are hidden from view) being of poor quality, having little or no mortar. An example of this is Bradway Tunnel near Sheffield.

16.5.5. Tunnel Surveys

The complex nature of these tunnels means that both non-intrusive and intrusive surveys are an essential prerequisite to electrification.

It is important to understand the shape of the section at all points within the tunnel by undertaking a point cloud survey (section 18.1.2) throughout the whole tunnel length. Coring of the brickwork will determine the overall thickness of the masonry, and if large diameter cores (typically 100 to 150mm) are taken they can be subjected to compression testing to determine strength. Mortar samples can be chemically tested to determine the ratio of sand, lime and cement; these can also be subjected to *X-Ray Diffusion* (XRD) tests, which although expensive give much more reliable results for mortar composition.

The eventual OLE fixing design can only be proven by undertaking a *pull-out test*, where a trial fixing is installed in the tunnel, left to cure, and then tested to destruction by applying an increasing axial load to the fixing.

16.5.6. OLE Design

The design of OLE in historic tunnels requires particularly careful thought, especially where masonry is in poor condition and/or suffering from water ingress. Significant remedial works may be required prior to electrification, including brickwork and mortar repairs, and diversion of frequent water flows using drip trays and pipework. Old brickwork may require significant intervention before it can accommodate the weight of the OLE supports. The nature of the water chemistry must also be understood; acid or alkaline soils will form acid or salt solutions which can attack OLE components, and tunnels running though marine environments

present even bigger challenges, with aggressive saline solutions and even marine microbial fauna[188] which will eat through metalwork.

For all of the reasons detailed above, each older tunnel requires an OLE configuration tailored to its shape and length. Where possible, tunnels use a conventional OLE system, with a small system height and more frequent support. Two track tunnels often use short cantilevers supported from the crown of the arch, with the drop tubes staggered along-track and across-track to provide sufficient room for each cantilever.

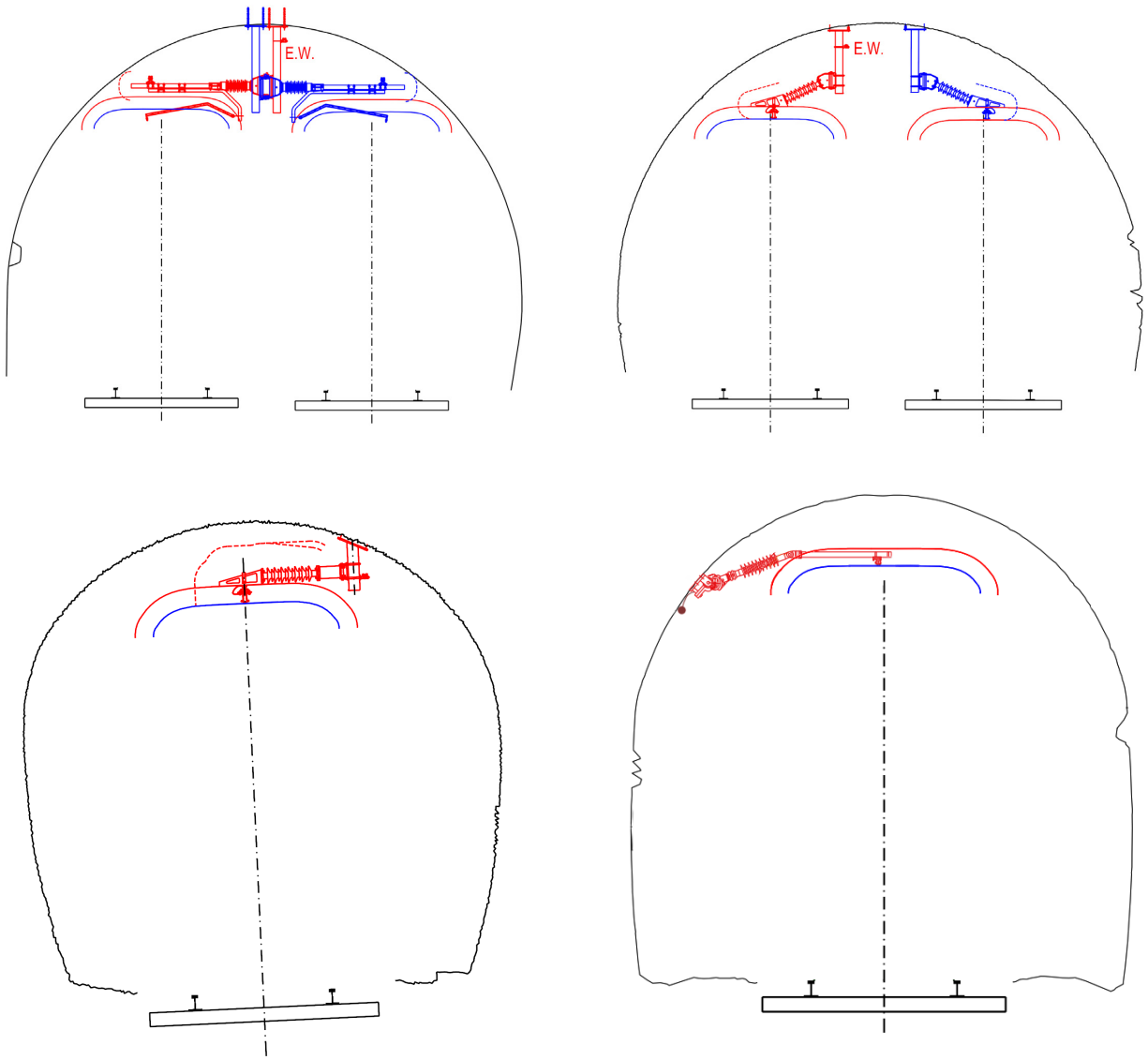


Figure 314: (clockwise from top left) OLE systems in older tunnels; two track bore with small system height conventional OLE, two track bore with ROCL, single track bore with tunnel arm, single track bore with ROCL

This is not possible in small single bore tunnels, which use either an elastic *tunnel arm* - which operates in much the same way as a bridge arm (section 11.10.9), but with a shape matched to follow the tunnel lining - or a ROCL configuration.

[188] The Severn Tunnel is a rare example of a tunnel under a saltwater estuary, and the mudflats of the estuary are home to *Sulphate Reducing Bacteria* (SRBs). These have been shown to make their way into the tunnel through water ingress points and then digest metal components. For more information see en.wikipedia.org/wiki/Sulfate-reducing_microorganism.

Figure 315: Rebosio twin contact elastic tunnel arm

Longer tunnels are unlikely to have sufficient room for the necessary tensioners (section 11.3), and unlike modern tunnels it is not possible to design a pocket for balance weights.

Figure 316: Small system height wiring in circular bore tunnel at major station throat; note opposing staggers and anchoring of additional wire runs. King's Cross, UK

The smallest historical tunnels face the same problem as that of their modern equivalent – that there is insufficient room above the train to accommodate a conventional cantilever. In this case, ROCL will be used.

16.6. Additional Tunnel Challenges

All tunnels face the problem of preventing insulators (section 11.18) electrically *tracking* by keeping them clean, since the normal self-cleaning action under rainfall is not available. This problem is worse in tunnels with a significant amount of diesel traffic, dust from mineral traffic or an aggressive atmospheric environment.

For tunnels using Auto Transformer Feeding (section 10.4.3) there is usually insufficient room to achieve ATF to earth and ATF to OLE air gap clearances (section 10.8), so an insulated ATF cable (section 10.2.9) is often

used, supported from the tunnel wall.

Earthing and bonding (section 10.10.1) in long tunnels often requires special measures, since the lack of OLE foundations means that a good connection to earth is not guaranteed.

16.7. Signalling

Key signalling interfaces are;

- Electrical clearances to signalling structures (from RCs, ATFs, OLE, and pantograph);
- Signal positions with respect to overlaps and neutral sections;
- Conflicts with signal sighting requirements due to OLE 'clutter';
- Earthing & bonding.

16.7.1. Signal Sighting

Most railways worldwide still keep trains apart by means of *line of sight signalling*, meaning that the driver must be able to clearly see signal indications in good time to act on their instructions. OLE equipment can interfere with the sight lines, meaning that the driver has less time to read and understand the signal. In the past poor signal sighting has caused accidents, and in the case of Ladbroke Grove (1999)[189] 31 people died in a head-on collision after a new OLE installation obscured a critical signal aspect. For this reason signal sighting is a critical element of the OLE layout design process (section 18.4.1). .

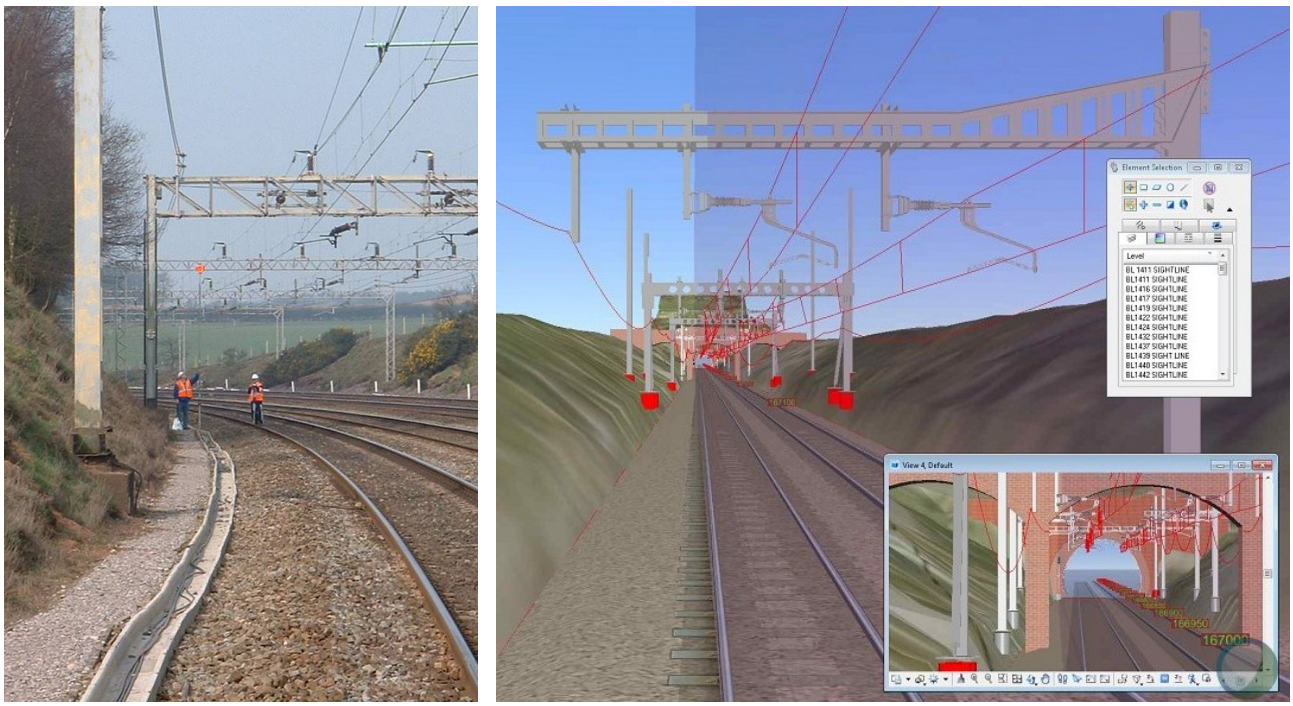


Figure 317: (l-r) Traditional and virtual signal sighting methods

16.8. Telecoms

Overhead line electrification has impacts on two existing groups of communication systems - those which are copper-based, and those which are radio-based.

[189] Accident report is available online at www.railwaysarchive.co.uk/eventsummary.php?eventID=142.

16.8.1. Electromagnetic Interference

In the UK the primary telecommunication network providing voice and data communications for the railway is the *Fixed Telecoms Network* (FTN). This copper system runs along most routes and links into a number of signalling assets such as location cases, *Principle Supply Points* (PSPs) and *Relocatable Equipment Buildings* (REBs).

The primary method of immunising these and any other copper telecoms cables from electromagnetic interference via OLE-generated inductive coupling (section 10.4) is to reduce the length of the circuits, terminating each in an FTN node before continuing with a new circuit.

UK routes are progressively replacing the copper FTN with the fibre optic-based *Fixed Telecoms Network - Next Generation* (FTNx), replacing the main backbone to provide higher bandwidth and the ability to use IP-based communications protocols. This also has the advantage of being completely immune to EMI. Copper is often retained at the interfaces with legacy communication systems.

A number of local telecoms systems at stations and level crossings can also be adversely affected by EMI, including:

- CCTV cameras;
- Public Address systems;
- Passenger Help Points;
- Customer Information Screens.

These may require additional shielding to prevent degradation or interruption of communications.

16.8.2. Radio Interference

Complementing the FTN system in the UK is the *Global System for Mobile Communications - Railway* (GSM-R) system. This is based on the GSM standard, and is used for voice and data communication between trains and railway control centres. GSM-R radio masts are placed at regular intervals along the railway and are linked to the FTN system.

GSM-R reception can be adversely affected by installation of OLE structures and reconstruction of adjacent overbridges, which can create *radio shadows*. Remedial measures are sometimes required, including installation of a higher gain antenna, increasing its height, adding repeaters or even an additional mast.

16.8.3. SCADA Interface

The introduction of new SCADA (section 10.7) for monitoring and control of OLE brings with it the need for additional telecoms capacity and infrastructure to provide communications between the ECR and the substation locations. Implementation of FTNx is advantageous, providing immunisation and also simpler communication, if an IP-based control and monitoring (10.7.4) system is being used.

16.9. Electrical & Mechanical Services

Electrical & Mechanical (*E&M*) *Services* include all non-electrification power supplies, as well as water courses, drainage, water and gas services. The key interfaces are:

- Signalling Supply Points;
- Earthing & bonding of LV systems and exposed metalwork;
- Overhead power wires;

- Gas & water pipes;
- Buried power cables;
- Telecommunication cables.

16.9.1. Signalling Supply Points

Signalling Supply Points (SSPs) are locations where a feed is taken from the OLE and used as a backup supply, usually for signalling power. This is done by means of a mast-mounted auxiliary transformer (10.2.5), with the primary winding connected between the OLE and traction earth, and the secondary winding providing an LV feed to a signalling power changeover panel. A removable 25kV fuse is provided on the primary side to protect the transformer from damage in the event of a flashover on that side.

Figure 318: (l-r) Signalling supply point with 25kV to 400V transformer, detail of 25kV fuse in drop-out link. Winkwell, UK

16.10. Stations

Special arrangements are needed at stations, due to the interface with a diverse (and sometimes unpredictable) general public. Typical restrictions at stations include:

- No live equipment over platforms;
- All live parts including the pantograph to be at least 3.5m stringline from platform surface (section 10.9)[190];
- ATF routing away from platforms or in protected ducting;
- Earth wire protection from vandalism;

[190] GLRT1210 "AC Energy Subsystem and Interfaces to Rolling Stock"; Issue 2, December 2019; RSSB; section 2.2.2.1. This standard permits live parts of the pantograph to infringe this clearance, subject to a site-specific risk assessment being completed.

- Anti-climbing measures (section 11.19.3);
- Integration of traction bonding with station LV bonding.

Figure 319: Earthed cantilever with no live parts over platform. Finsbury Park, UK

It may be necessary to apply special arrangements in order to meet standing surface requirements - this can include special earthed cantilevers or opposing staggers to keep live equipment sufficiently far away from the public.

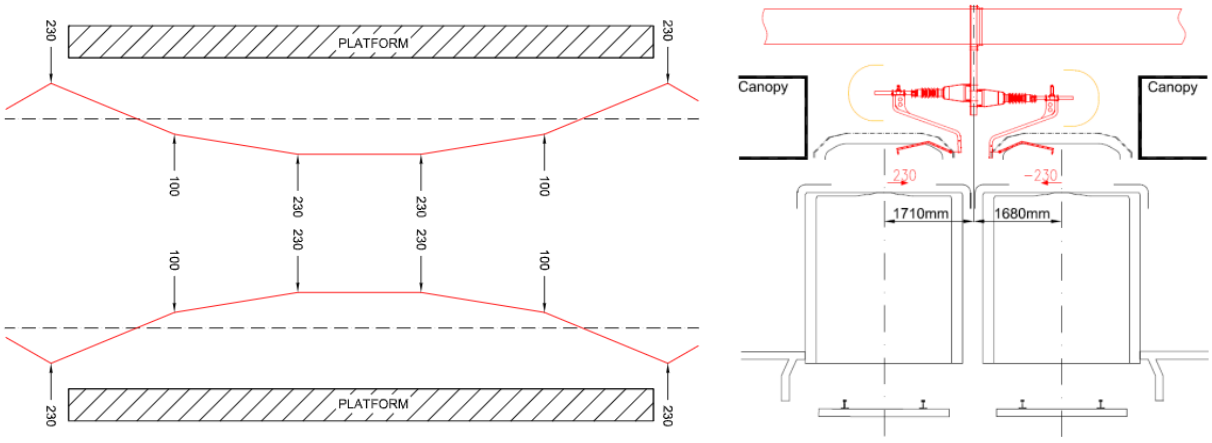


Figure 320: Opposing stagger arrangements for stations

16.11. Highways

The key interface with highways for mainline railways is at level crossings. Special safety arrangements are needed wherever OLE crosses a public right of way. National standards will typically specify minimum wire heights to be observed under all environmental conditions, based on national road vehicle height standards and typical crossing usage. For instance, UK standards[191] specify 5.8m as the minimum wire height for all road

[191] Ibid.; section 3.1.5.

crossings, and 5.2m wire height for foot and bridle crossings.

Figure 321: Typical hazards at an electrified level crossing. Enfield, UK

It should be noted that many vehicle crossings in the UK are for private access to farmland, and as such the user may be regularly crossing with over-height vehicles. It is therefore important to risk-assess each crossing prior to undertaking the OLE design, to ascertain what control measures are needed to protect both crossing users and the railway. Additional mitigations may be imposed, such as height barriers on the road approach to the crossing.

A further consideration for the many *user-worked* crossings in the UK is that they rely on the pedestrian crossing user to visually check for trains before crossing. OLE masts can reduce the user's *sighting distance*, and so a sighting assessment must be undertaken similar to that for signal sighting (section 16.7.1). This may recommend the relocation of OLE masts to improve sight lines, but ultimately the best mitigation is crossing closure in conjunction with an alternate means of safely crossing the railway. This is often not possible due to legal restrictions, in which case *Miniature Stop Lights* (MSLs) may be fitted to give crossing users a warning of approaching trains.

For tram and trolley systems, highways interfaces are multiple and complex.

16.12. Overhead Power Lines

Overhead power transmission lines frequently run alongside and across electrified railways. Most electricity supply administrations impose clearance requirements at all such crossing points. These typically take the form of minimum air gap clearances between all conductors in the transmission line[192] and all OLE parts - live or dead - under all conditions for both systems.

[192] The worst case condition for fixed termination power lines is generally the high ambient temperature/maximum power demand scenario.

Figure 322: 400kV power transmission line with OLE graded down to maintain clearances. Didcot, UK

In the UK these requirements are encoded in a national agreement between the supply industry and the railway[193] as follows:

Transmission Line System Voltage (kV)	Minimum Clearance (m)
≤ 33	3.0
66	3.0
132	3.7
275	4.6
400	6.1

The process of raising an overhead power line becomes more costly as voltage rises, and the opportunities for switching off the electricity network to do so become more limited. Sometimes the necessary clearance can be achieved by increasing the tension in the power line conductors; if this is not possible then it is usually necessary to erect a new pylon to increase the height.

For higher voltages it can often be more cost-effective to treat the power line in the same way as an overbridge, and grade the OLE down (section 11.13.1) to meet the clearance requirement. For lower voltages (such as the 11kV, 22kV and 33kV wooden

Figure 323: 33kV power transmission line - transition of aerial to buried cables on approach to an electrified railway. Swindon, UK

[193] Technical Specification 43-8 "Overhead Line Clearances"; Issue 5, 2019; Energy Networks Association Operations Directorate; section 8, table 6.

pole routes common in the UK) the low height of the poles will usually mean that the overhead crossing must be replaced with an under-track crossing before the route can be electrified.

The potential exists for induced voltages wherever power transmission lines either cross OLE at an oblique angle or run parallel in close proximity for a significant distance. This can lead to unsafe voltages being present in the OLE during an isolation. It may be necessary to provide additional DEP facilities (section 10.12.1) either side of the crossing point, or for the length of the parallel section.

16.13. Environment

Environmental interfaces include:

- Visual impact;
- Ecology and flora impacts;
- Vibration and noise impacts on local people.

This is discussed further in section 17.11.

17. The Planning Phase

When carrying out an electrification project of any kind, it is essential that the works are carefully planned and executed. Section 16 shows that OLE has significant interfaces with almost all other railway subsystems; failure to carefully plan OLE works will inevitably result in cost and time overruns, as well as potential for unmitigated safety hazards and incidents. The process of planning an electrification project involves multiple disciplines, since the whole railway is affected by the introduction of OLE.

An electrification project should be seen as a production line, one which starts in the planning office and finishes with Entry Into Service (section 20.8). Delays at any stage of the process will affect completion dates and costs, and each step of the process requires careful management.

In this section and section 18 the drawings and documents described form a hierarchy; each overlaps with the one above and below in terms of information. This hierarchy is described in descending order.

17.1. Types of Electrification Projects

Overhead electrification projects can broadly be split into three categories:

- New electrification - implementation of OLE along a previously non-electrified route;
- Renewal of electrification - mid-life refurbishment of an OLE system to improve reliability, extend lifespan and eliminate known failure modes;
- Modification of an existing electrified location or route to support a wider railway project, such as capacity increase, junction remodelling, platform extensions and other infrastructure modifications.

The following sections focus on new electrification at 25kV AC on an existing mainline railway, but many of the activities described are also needed for the other types of project.

Planning of new electrification is critical to the success of the design and construction phases, which should not start until the planning is complete. A project may spend a significant amount of time in this phase, and this can often allow the subsequent phases to proceed more quickly and result in a quicker entry into service.

17.2. Project Goals and Requirements

The first step in any electrification project is to clearly articulate its aims. This is typically codified as a series of requirements in a *Project Requirements Specification*. Requirements for a new electrification or electrification renewals project should include:

- Operational factors, including the number of and type of electric trains to be supported, their routes, speeds and stopping patterns;
- Future capacity allowances;
- Electrified depot and stabling facilities;
- Traction power demand, including how and where it will be supplied;
- Route reliability, broken down to system level;
- Maintenance access;
- Interoperability;
- Pantograph interface (section 11.1.2) requirements;
- Standards to be applied to the project;
- Interfaces with adjoining projects and routes;
- Any interim stage electrification limits;

- *Reliability, Availability, Maintainability and Safety* (RAMS) targets.

Requirements should be high level and output-based - that is, specifying what outputs are required rather than how those outputs are to be achieved. Each requirement should be clearly articulated, deal with a single aim, and be measurable. Supporting this document is the *Lines To Be Wired Diagram*, which provides a schematic overview of the end state of the project. This should include any diversionary routes which require electrification to retain resilience during planned or unplanned disruption.

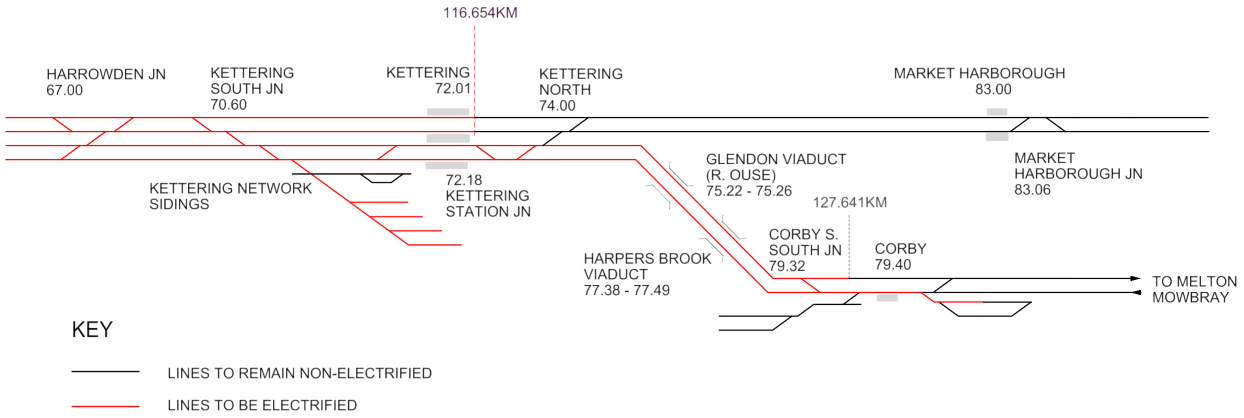


Figure 324: Extract from Lines To Be Wired Diagram

The traction power engineer should be consulted during the development of the project requirements to ensure that they are sufficiently detailed for the traction power modelling to begin. The planning process should not proceed beyond this point until the requirements and wiring extents have been formally authorised.

As well as defining the core lines to be electrified, consideration must be given to non-electrified lines which diverge from, and converge with, the electrified lines. Depending on the signalling and traffic management system to be used, there may be a small but significant risk that an electric train is accidentally misrouted onto a non-electrified line. In this case *overrun protection* will be provided in the form of a short section of live operational OLE on the non-electrified line[194], to provide protection against dewirement as the pantograph leaves the electrified line. This protects both OLE and pantograph from damage, and facilitates recovery of the electric train. This provision is generally only provided for tracks with a permissible signalled move from the electrified to non-electrified line.

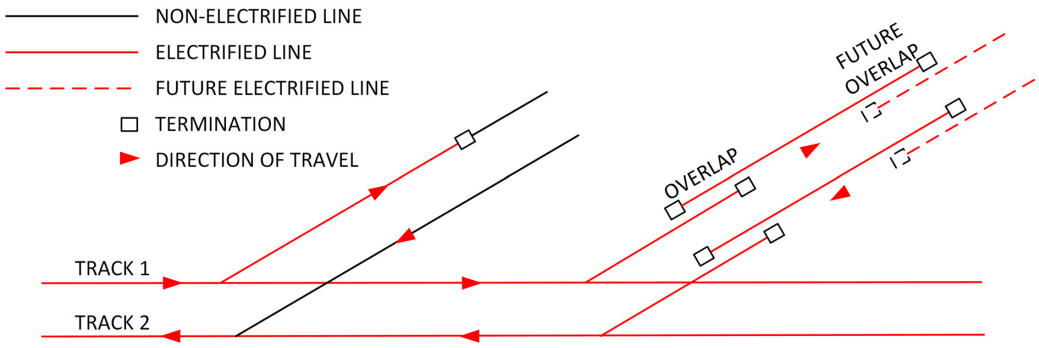


Figure 325: (l-r) Overrun protection, and passive provision for future electrification

At key junctions it may be necessary to go further and provide full passive provision for future electrification

[194] In the UK the standard provision is 7.5m of OLE per km/h of diverging linespeed. NR/L2/ELP/27715/02 "Overhead Contact System Design Specification: Allocation Design Principles"; Issue 1, March 2018; Network Rail; section 13.

of the diverging route. In this case the provision is expanded to cover both diverging and converging tracks, and the extent can be increased to provide a complete half tension length (section 11.4) on all lines, which can later be temporarily converted to a permanently earthed section (section 10.12.2) during construction of the new electrified line. This allows construction to be undertaken without isolation of the existing route. The additional OLE will be terminated at an overlap to facilitate future extension.

17.3. Operations and Timetable

It is essential to assess the expected power demand both in the short term, and several years into the future, allowing headroom for future growth and recognising that electrified railways often attract new customers due to the sparks effect (section 7.3.3). This process is known as *power modelling*.

Traditional power modelling has focused on development of a notional timetable, which must incorporate potential electric freight as well as passenger services - since freight is particularly demanding on the traction power system (section 10). The development of this timetable is itself a complex process, and unlikely to reflect the actual timetable many years into the future. A better approach is therefore to base the modelling on generalised traffic patterns, train types and frequencies rather than specific trains and timetables. Any future aspirations to extend electrification should also be allowed for as far as possible.

17.4. Power Planning

The completion of the wiring extents and expected electric train services allows the development of the power system to begin. This can start prior to completion of the project requirements, and may indeed influence them. It is important to understand the demarcation between the three elements of the electrification system:

- The *traction power system* - all of the elements owned by the DNO or NGC (section 10.1.3) up to and including the supply transformers (section 10.2.2);
- The *Power and Distribution* (P&D) system - all of the elements owned by the railway infrastructure manager between the output of the supply transformer and the lineside sealing ends (section 10.2.9);
- The OLE system from the sealing ends to the train.

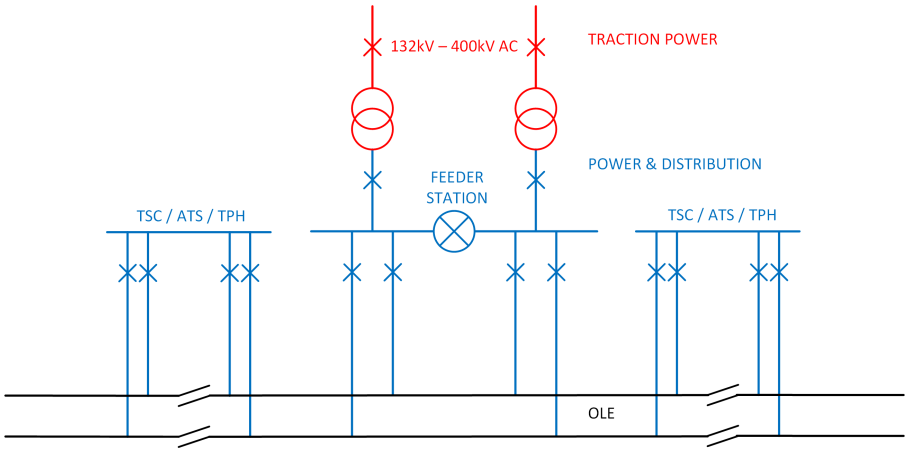


Figure 326: Demarcation between traction power, power & distribution and OLE

This differentiation is crucial because the contracting strategy is different for each of them. The traction power system is funded and procured by the railway infrastructure manager, but designed, built and managed by the DNO or NGC (depending on voltage); whereas the power and distribution system is generally designed and built by a specialist HV power equipment supplier, but operated and maintained by the railway. The OLE is generally designed and built by a specialist contact systems installer, but operated and maintained by the railway.

17.4.1. Grid Supplies

The process starts with the identification of potential grid feeding locations, taking into account the ESI networks (section 10.1.3). Any such locations must be confirmed as having the required supply capacity, unless a local grid upgrade project can be developed in tandem with the railway electrification project. This is necessarily an iterative process, since the definitive capacity requirements will not be known until the power simulation (section 17.5.1) is complete. Grid locations are often some distance from the railway that is to be electrified, in which case an appropriate aerial or buried cabling route should be identified. Regardless of the location of the grid site, a suitable and available piece of land must also be identified alongside the railway to accommodate the railway feeder station. Depending on the specifics of the site, the ESI compound containing the supply transformers (section 10.2.2) may be co-located alongside the railway substation or sited remote from it. The ESI has specific legal powers that make it easier to gain land-take and wayleaves, so they will often lead the selection process, proposing the best connection points and consulting with the infrastructure manager to develop the optimum supply arrangements.

17.5. Equipment Philosophy

As part of the power planning process it is necessary to begin to make choices about the equipment types that will be used, in terms of:

- Brick-built, modular or containerised building (section 10.2.1);
- Indoor or outdoor switchgear (section 10.2.7);
- Air-insulated or gas-insulated switchgear.

These choices significantly affect the size of the substation and therefore the feasibility of the proposed locations.

17.5.1. Initial Feeding Configuration and Power Modelling

The identification of feeding locations allows the development of an *initial feeding configuration*. This includes the identification of notional FS, TSC and MPTSC sites for a classic system (section 10.4.4), or ATFS, ATS and MPATS sites for an AT system (section 10.4.3). At this stage the choice of classic or AT feeding may not be defined, and options can be developed for both systems to determine whether a classic system can support the planned timetable. It is important at this stage to focus on the feeding requirements in terms of voltage regulation, and to exclude sectioning requirements (section 17.6). This approach maximises the efficiency of the initial feeding design.

At this point it is essential that the theoretical locations of FS, MPTSC, ATFS and MPATS sites and their associated neutral sections (section 11.6.3) are tested against the physical realities of the railway. It is often the case that the locations which provide the ideal electrical outcome do not have space or land provision available for a substation. Buried or aerial feeds between the grid site and the railway, which can require land-take or wayleaves, also need to be considered. Neutral sections have their own constraints, and matching a feeder station site to a suitable neutral section site can often be challenging. These constraints must be fed back into further modelling iterations until a compliant, practical and cost-effective outcome is achieved.

It is also necessary to consider how any electric depot will be fed; although simply using the OLE into the depot as the feed may be acceptable, this can mean loss of power to the depot when the adjacent mainline OLE is isolated. Some depots are provided with their own dedicated circuit breaker or feeder station to permit depot operations to continue independent of the mainline.

The resulting substation locations, together with the track layouts, are used to build a *power model* using specialist modelling software. This software allows the railway to be modelled as a complete traction power system, and crucially includes the ability to simulate the running of the timetable, including the

minute-to-minute movements of the electrical loads along the railway, as well as their changing power demand as trains accelerate and brake.

The power modelling assesses both normal and N-1 (section 10.1.3) feeding requirements; it is normally the N-1 feeding arrangements that identifies any voltage regulation problems. Low voltages can occur due to the extended feeding length, or currents in a track feed or OLE conductor can be higher than the system rating. The modelling also takes into account isolations for maintenance access to equipment, including any bypass feeding which is necessary to maintain supplies elsewhere.

These simulations are designed to expose weaknesses in the initial feeding configuration, and usually result in modifications being needed to it. The modified configuration is then modelled to confirm that it meets the requirements. Care should be taken to avoid too many iterations, in case the system becomes locked to a specific timetable, with insufficient capacity for unforeseen future demand.

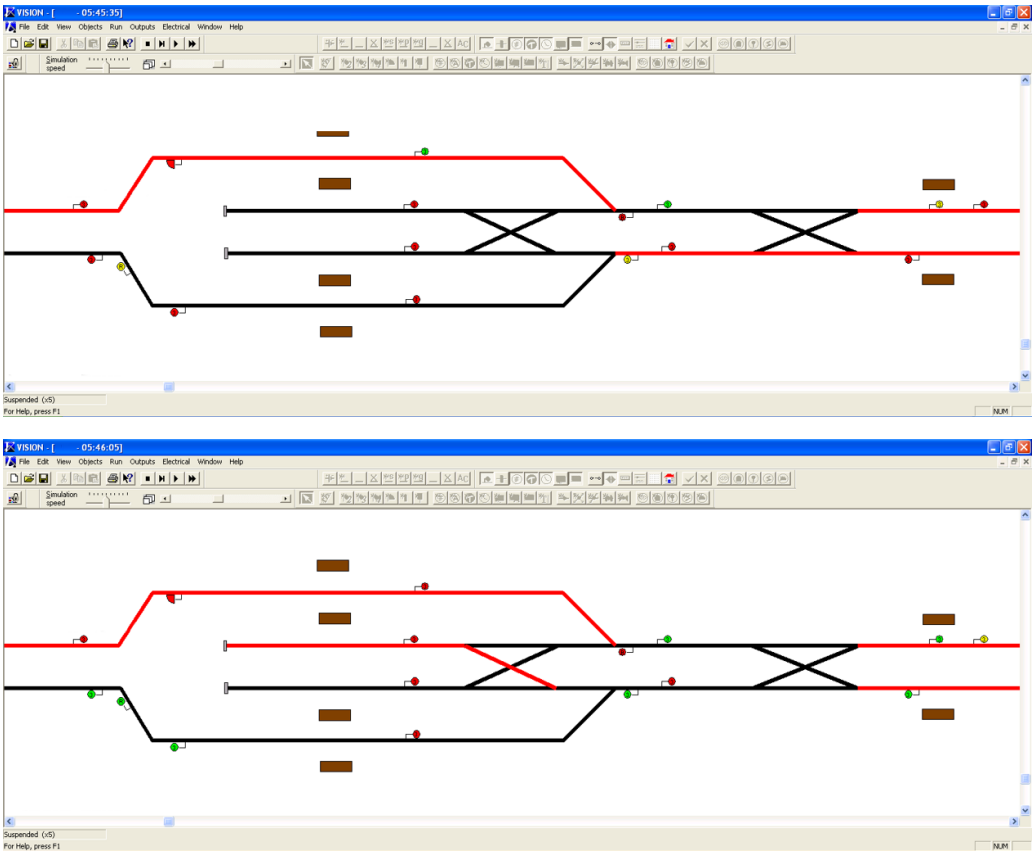


Figure 327: Power modelling with different train positions (shown in red)

The power modelling also defines the rating of the various AC supply equipment components (section 10.2); the electrical and physical parameters must be agreed by the OLE and P&D designer to ensure that the same electrical and environmental assumptions are used in both the P&D design (section 18.2) and OLE system specification (section 17.9.1).

As the feeding configuration develops, it will begin to be documented in the *Major Feeding Diagram* (MFD). This diagram shows the interface between the electricity supply authority and the railway; feeder stations, TSCs, AT sites and neutral sections are included.

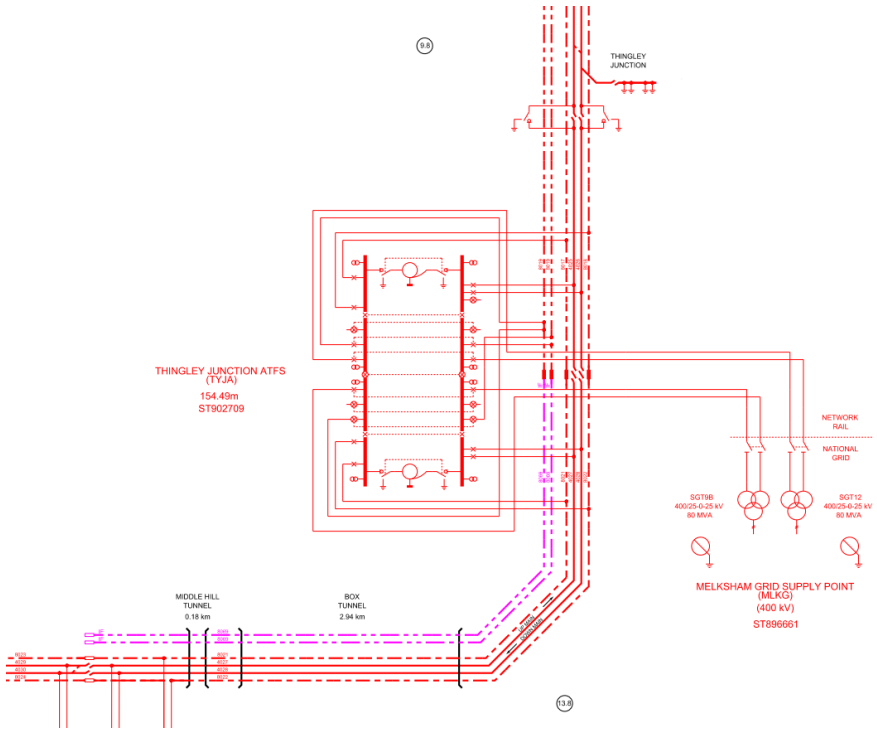


Figure 328: Typical MFD detail

The MFD will typically pass through a number of iterations as the project develops, reflecting changes driven by the design of the feeding and switching sites, and the availability of additional detail as subsequent design development is completed.

17.6. Sectioning Arrangements

Once the MFD has reached a stable feeding configuration, the development of the *sectioning arrangements* should be undertaken. This process defines all of the required sectioning locations, including those at TSCs or AT sites, as well as TSS sites (section 10.3).

It is necessary at this point to select a general sectioning philosophy. Sectioning in the UK has traditionally been based on major sectioning carried out at TSCs, with these located at regular intervals; and a TSC located at every significant junction where two electrified routes diverge, or indeed a non-electrified route diverges which may be electrified in future. Additional sub-sectioning locations were provided between TSCs using non-load-break isolators (section 11.7).

The advent of IP-Based Control and Monitoring (section 10.7.4) has challenged this philosophy, with the ability to automate the fault-finding and clearing process meaning that the same level of electrical protection can be provided with fewer busbars and circuit breakers. Some new electrification projects are now being planned fewer TSCs or SATS - instead TSSs are provided with load-break isolators and these are used to clear faults in conjunction with circuit breakers at the FS, MPTSC, ATFS and MPATS sites.

The sectioning requirements of an electric railway are heavily influenced by train service patterns, stabling requirements and other requirements of the trains operators, as well as those of the infrastructure maintainers when taking isolations. Sectioning points should be aligned with signals controlling possession limits to prevent inadvertent re-energisation (section 10.12.1), and decisions are required on which isolators (section 11.7) should be motorised. As with neutral section locations (section 17.5.1), all proposed sectioning locations must also be checked for OLE feasibility before they can become part of the section diagram. Any normally open section breaks (whether insulated overlap or section insulator) must additionally be checked against the location of controlled signals so that the pantograph of any stopped train will not bridge the sectioning point;

this can result in arcing and potentially cause a wire burnout.

For these reasons the development of the sectioning arrangements requires a collaborative approach, including representatives from the operation and maintenance organisations as well as P&D and OLE and signalling engineers.

It should be noted that any changes to TSC, MPTSC, ATS or MPATS locations during this process do not invalidate the traction power design (section 17.5.1), and it is generally not necessary to renegotiate with the DNO or ESI as long as overall power demand has not changed.

17.6.1. Electrical Section Diagram

The resulting *electrical section diagram* - often shortened to *section diagram* - is based on the Lines to be Wired Diagram (section 17.2) and MFD (section 17.5.1) and shows the detailed electrical feeding & sectioning. It details switch numbers and locations, booster transformers, section numbers, and protecting signals. The drawing will be in a preliminary state at the start of the project, and structure numbers and other details will be added as the detailed design progresses.

17.7. Enabling Works Planning

At the planning stage of the project, it is essential to identify all of the *Enabling Works* interventions that are required to railway and non-railway assets to permit electrification to proceed. These include assessment of:

- All overbridges and tunnels to determine any reconstructions, track lowers or track slews that are required to provide electrification clearances;
- Suitability of all bridge parapets to protect against electrical safety hazards (section 10.9);
- Immunisation readiness of signalling and telecoms assets;
- Clearances and separations to existing signal posts and gantries (sections 10.8 and 10.9);
- Initial signal sight lines (section 16.7.1) to determine any major conflicts;
- Clearances to overhead ESI transmission lines (section 16.12);
- Any electrical clearance or electrical safety issues at stations that need resolution - for instance cutting back of canopies;
- All vehicle and foot level crossings to determine safe clearances and any required sighting lines (section 16.11);
- The relationship between overbridges, level crossings and stations to ensure that compliant contact wire gradients (section 11.13.1) are achievable;
- All buried or overhead services (gas, water, electricity and telecoms - see section 16) that need avoidance or diversion during the works;
- Any areas of geotechnical instability due to poor earthworks (section 18.1.3);
- Any mine workings which could affect geotechnical stability;
- Any civils structures - such as viaducts and cutting walls - needed for support of OLE structures;
- Integrity and suitability of all existing fencing;
- Vegetation management (section 19.8).

The goal of the project team during this stage must be to identify and then minimise the extent of these *route clearance* and *signalling immunisation* works, since they can account for anywhere between 25% and 50% of the total cost of electrifying a route, and implementation of these works must take place well in advance of OLE construction (section 19). Local authority permission is often needed for bridge works, so time for planning application and consultation must also be factored in to the programme (section 17.13). The output of the

planning process will typically be a set of feasibility and option selection assessments, to determine the most cost-effective ways of preparing the route for electrification.

17.7.1. Telecoms Immunisation, Earthing and Bonding and EMC Strategies

It is essential that the telecoms immunisation and bonding designs (section 18.4.7) are treated as part of a single integrated cross-discipline process, since many non-electrification assets need to be bonded, and there is usually a complex interplay with third party (DNO) earthing systems. The development of an *Earthing and Bonding (E&B) strategy* takes place in the planning phase, and this sets out the principles and general arrangements that are then followed in the bonding design. EMC sources and victims (section 10.4) are also identified at this stage, and the mitigation principles set out in the *EMC strategy* for the project.

The output of the power modelling (section 17.4) is used to assess the unmitigated impact of EMI on the various lineside assets along the route. This is typically undertaken by feeding the data from the power model into a more detailed *multi-conductor simulation* which calculates the current flows in each of the OLE conductors over time as electric trains move along the route. This simulation then calculates the electromagnetic fields, induced voltages and touch potentials (section 10.10.1) generated by the OLE in the rails, telecoms cables and other conductive lineside assets. The E&B strategy is developing based on this information.

The simulation outputs are also used to develop the *telecoms immunisation strategy* and define the work that must take place prior to energisation of the OLE. The full definition of this work is outside the scope of this book, but the work typically begins with a detailed survey of the telecoms assets, whether copper-, fibre optic- or radio-based.

17.8. Track Position Strategy

A key dilemma for the OLE designer is that the contact wire position is measured relative to track, which can and does move over time, but mast positions are fixed in space. It is common for track to move tens of millimetres between the walkout survey (section 18.4.2) and installation of the wire runs (section 19.12), due to the track forces imparted by trains or maintenance interventions such as *tamping*. This movement renders the designed support and registration geometry invalid, and the necessary rework can seriously undermine construction efficiency.

For this reason it is essential that each project develops a track position strategy, aimed at minimising this rework. This can be based on a *managed track position*, where the track is maintained within an agreed distance of an approved design alignment. Regardless of the strategy selected, it is essential to agree it with the track maintainer at an early stage of the project, to avoid complications during construction.

17.9. The OLE Design Catalogue

There are three stages of OLE mechanical design which must be undertaken before construction can be started. The first two stages should be completed during the planning phase, and together provide a design catalogue that can be used during the design phase (section 18). This ensures that the design phase can be executed in an efficient manner, without the risk of rework due to changes in the OLE catalogue.

- *System design* is the matching of mechanical and electrical parameters to a railway performance specification, to produce basic wire run parameters (wire sizes and tensions) - with a typical output being a system description manual;
- *Basic design* is the creation of components and assemblies for a system, together with detailed geometry and load rules - typical outputs being basic design drawings (section 17.9.2).

17.9.1. OLE System Specification

The correct selection of an OLE system is an essential prerequisite to a successful new electrification project. The chosen system must provide safe, reliable performance and be compatible with both the infrastructure and the rolling stock for the route. Specific compatibilities to check when selecting a system include:

- Rolling stock formations and pantograph spacings;
- Train speeds;
- Pantograph types (section 11.1.1);
- Electrical loads and their impact on conductor sizes;
- Environmental conditions, including ambient temperature range (section 11.3), wind (section 11.9.1) and ice conditions (section 11.9.2) and their impact on system geometry and loadings;
- Track configuration and geometry;
- Route topography;
- Requirements to meet TSIs or NSTNs (section 11.1.2);

Most administrations have one or more existing system designs (such as those in section 13) for use on new electrification - for mainline railways, these are typically categorised into low, medium and high speed variants. If no OLE system design exists which meets the requirements of the project, it is necessary to develop a new one - or preferably, modify an existing one, since this reduces the amount of time that the development will take.

17.9.2. OLE Basic Design

The assemblies and components to be used on the project must support the aims of the system design (section 17.9.1), while being reliable, affordable, and so far as is practicable, maintenance free. Again, most infrastructure managers will have basic design ranges in place for use on electrification projects, but it is common for each new project to add specific assemblies to solve problems specific to the topography or environment of that route. Basic design ranges can either be proprietary - that is, licensed from a specific OLE manufacturer - or designed and owned by the infrastructure manager. The advantage of a proprietary system is that the designs are proven and available, with existing supply chains in place. The disadvantage is that a licensing fee is typically levied, and the administration is locked into using that manufacturer for spares and modifications. With a wholly owned basic design, there is no licensing or lock-in, but the administration is required to develop its own designs and supply chain, with the risk that the resulting assemblies are not reliable. Most modern systems are a hybrid of the two, comprising proprietary items where mechanical reliability and/or complexity is high[195], and self-designed components for lower risk items.

17.10. OLE Wiring Planning

With the power planning (section 17.4) complete and an OLE catalogue selected, the planning of the OLE wiring in accordance with the Lines to be Wired Diagram (section 17.2) can begin. This process pinpoints the insulated overlaps (section 11.4.2) necessary for the sectioning points detailed in the Section Diagram (section 17.6.1), as well as all intermediate construction overlaps according to the maximum tension length (section 11.4) specified in the OLE System Design (section 17.9.1).

[195] Common proprietary items include cantilevers, insulators, registration arms, section insulators, neutral sections, isolators, bridge arms, droppers and tensioning devices.

17.10.1. Wire Run Diagram

The resulting *Wire Run Diagram* is a schematic showing the wire run numbers and their indicative anchor locations for a given route. The diagram also identifies the *Construction Units*[196] (CUs) - running from overlap start to subsequent overlap start - which are used to plan the OLE design and construction phases.

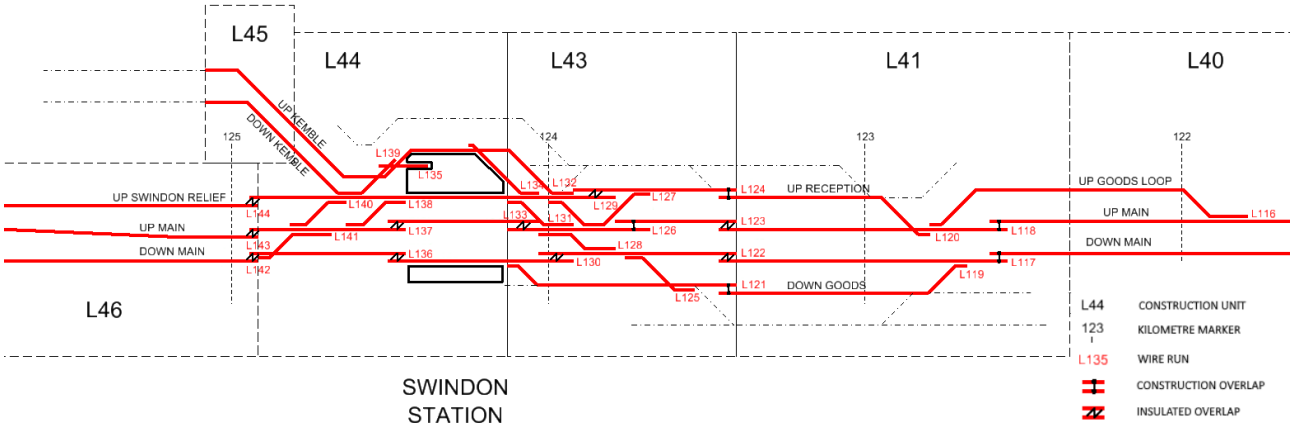


Figure 329: Typical wire run diagram detail

17.11. Environmental and Consents Constraints

Electrification projects have multiple impacts on the environment through which they pass, and these must be managed and mitigated. Environmental legislation varies from country to country, but most jurisdictions will impose constraints on what the project is permitted to do, and the times of day or year when it is permitted to do them. It is essential to have a full understanding of these during the planning stage, as there are likely to be *legal consents* required before certain activities can take place, and obtaining these consents can be a lengthy process. The constraints will also have impacts on construction sequencing and task durations.

In the UK the environmental planning process begins with an *Environmental and Social Appraisal*. This captures all of the potential areas that must be assessed during the planning process. Potential impacts fall into a number of categories listed below. Once all of the potential impacts are identified, an *Environmental Management Plan* is created to capture all of the required mitigation processes.

17.11.1. General Environmental Impacts

General environmental impacts of electrification construction activities include:

- Construction dust;
- Use of oil and fuel, with attendant risk of spillage and contamination of land or water courses;
- Use of hazardous substances;
- Disturbance of contaminated land;
- Existing flood risk (such as at substation sites) or increased flood risk (for instance as a result of a track lower);
- Generation of waste such as arisings from piling (section 19.4).

17.11.2. Ecology

Ecological impacts of electrification can include:

[196] Sometimes known as *Track Units*.

- Impact of vegetation management (section 19.8) on wildlife and nesting birds;
- Changes to water courses as a result of drainage diversions;
- Impacts on protected species[197] due to foundation, overbridge fixing or viaduct fixing installation;
- Disturbance of invasive species[198] or species harmful to health[199] during construction.

Protected species may need to be relocated before intrusive construction activities such as piling can start, and this process can only take place when the animals are not hibernating or breeding. Some trees have *Tree Preservation Orders* (TPOs) placed on them, restricting what is permissible in terms vegetation management on them.

17.11.3. Conservation

Many natural and manmade features in the landscape enjoy legislative protections, and these must be identified and any impacts from electrification eliminated or mitigated. UK locations include:

- Sites of Special Scientific Interest (SSSIs);
- Special Areas of Conservation (SACs);
- Special Protection Areas (SPAs);
- Wetland sites protected under the *Ramsar Convention*;
- Areas of Outstanding Natural Beauty (AONBs);
- National Parks;
- National Nature Reserves;
- Local Nature Reserves;
- Ancient Woodland Sites;
- Listed buildings;
- Scheduled ancient monuments;
- Conservation areas;
- World heritage sites.

17.11.4. Local Neighbours

Electrification construction inevitably impacts on people living in the vicinity of the affected route, and care must be taken to minimise those impacts, while communicating and consulting with neighbours before, during and after the work.

Typical impacts of electrification construction include:

- Noise and vibration from piling (section 19.4.2), excavation, drilling (section 19.5.1) and depot activities (section 19.2.1);
- Night time disturbance from construction activities, including noise and temporary lighting;
- Additional lorry movements to depots and access points (section 19.2.1);
- Temporary or permanent use of third party land;

[197] Protected species in the UK include bats, badgers, dormice, breeding birds, reptiles, great crested newts, fish, otters, water voles and crayfish among others.

[198] Invasive non-native species cause problems by crowding out other native species. The most common UK example that affects electrification construction is Japanese Knotweed, but there are several others.

[199] Giant Hogweed is the most common harmful species in the UK; contact with the plant causes phytophotodermatitis, a chronic illness resulting in blisters and scars.

- Temporary or permanent diversion of roads or footpaths (section 16.11), and curtailment of access for members of the public and business.

17.11.5. Consents Options

Depending on the national and local laws in place, a number of legal avenues can exist for obtaining the required consents for the works. In the UK there are national consents mechanisms such as a *Transport and Works Act Order* (TWAO), which require planning proposals to be lodged with national government, which then undertakes a formal consultation process on the proposals, accepting objections from interested parties. Often these objections will result in changes to the proposal to mitigate the impact.

A second national option is the *hybrid bill*. This is typically used for construction of new electrified railways, and follows a process where proposals are lodged before both houses of parliament, which will review and either pass or reject the proposal.

The third option is to go without a national consent, and instead seek planning permission from individual local authorities. This approach has been used on all recent UK electrification schemes, but has the significant disadvantage of requiring multiple separate consents processes with multiple statutory bodies. The multitude of separate processes introduces programme risk (section 17.13.3), and can have a negative impact on project efficiency.

17.11.6. Embodied Carbon

The embodied carbon (section 7.3.3) generated by electrification construction should be considered, and where possible, minimised. However it should be noted that the magnitude of these emissions is heavily outweighed by the carbon savings generated by running electric trains in place of diesel trains[200]. The necessity of keeping electrification cost-effective (section 7.5) must always be borne in mind, since replacement of conventional steel and concrete with more expensive low-carbon alternatives can shift the cost-benefit ratio of electrification to the point where schemes will not be authorised and the net carbon savings not realised.

17.12. Hazard and Risk Assessments

During all of the planning activities detailed above, multiple new hazards will be identified due to the introduction of electrification, and the asset interventions required to enable the works. These hazards can manifest at any stage of the electrification lifecycle; during construction, operation, maintenance or demolition. All of these should be captured in a series of hazard assessments, which will proactively identify all hazards. A project may conduct formal *HAZard IDentification* (hazID) workshops, bringing stakeholders together to systematically consider aspects such as equipment functions, risk to exposed populations, and interfaces - both in normal operation and in the event of failures.

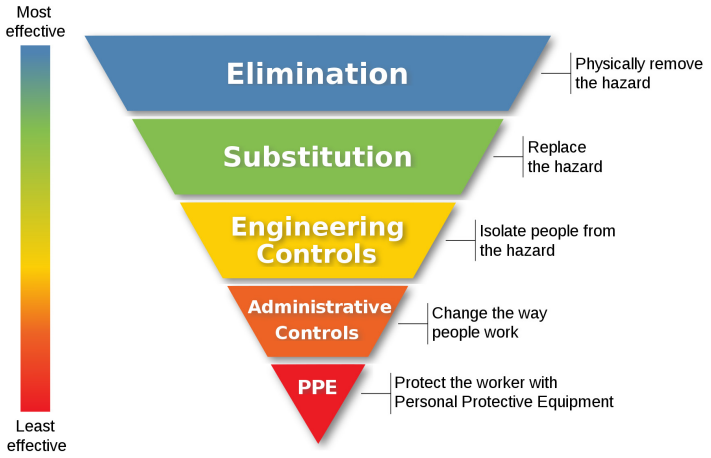


Figure 330: Hierarchy of hazard controls

[200] "Why Rail Electrification?", Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; section 3.3

The results of this process will feed into a risk assessment process aimed at eliminating hazards wherever reasonably practicable, and mitigating those which cannot be eliminated. The hazard and risk assessments will be reviewed and updated at key points during the planning, design and construction phases. Any *residual hazards* that cannot be eliminated in the design phase should be clearly recorded on the drawings, and any that remain at project completion should be recorded in the *Health and Safety File*.

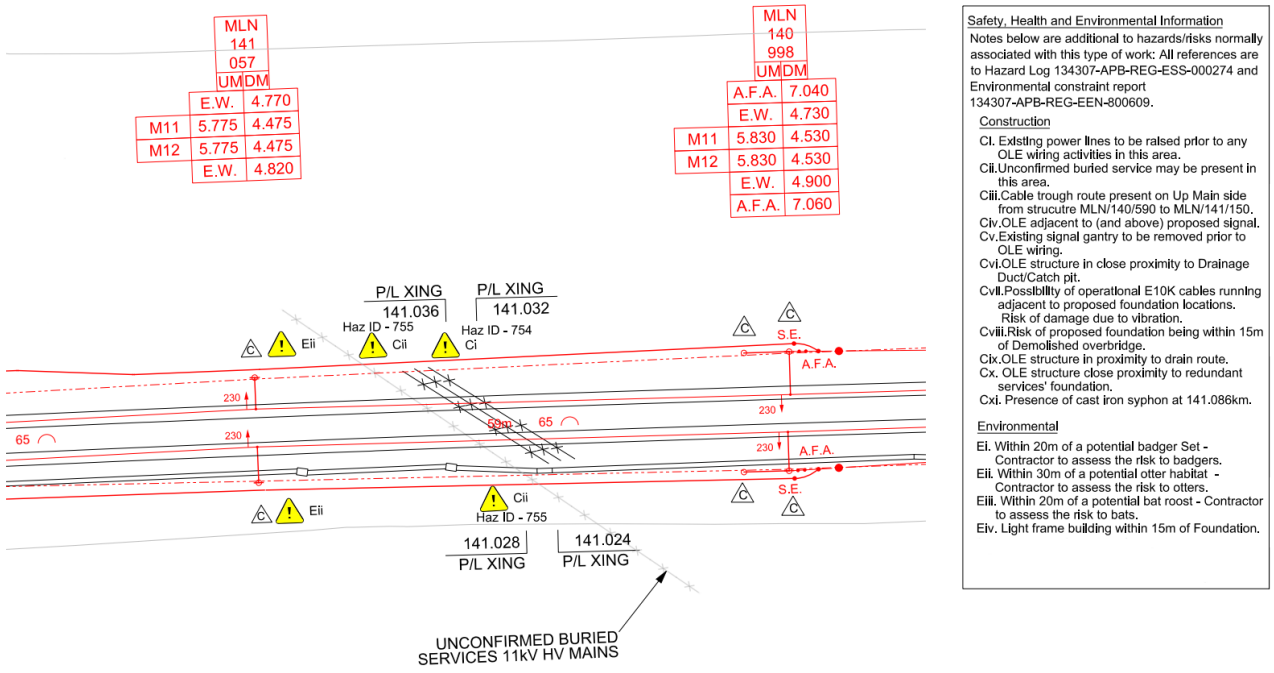

MLN 141 057
UM DM
E.W. 4.770
M11 5.775 4.475
M12 5.775 4.475
E.W. 4.820
MLN 140 998
UM DM
A.F.A. 7.040
E.W. 4.730
M11 5.830 4.530
M12 5.830 4.530
E.W. 4.900
A.F.A. 7.060
P/L XING 141.036
Haz ID - 755
P/L XING 141.032
Haz ID - 754
Eii
Cii
Ci
S.E.
A.F.A.
230
65
53m
141.028 P/L XING
141.024 P/L XING
UNCONFIRMED BURIED SERVICES 11kV HV MAINS
Safety, Health and Environmental Information
Notes below are additional to hazards/risks normally associated with this type of work: All references are to Hazard Log 134307-APB-REG-ESS-000274 and Environmental constraint report 134307-APB-REG-EEN-800609.
Construction
Ci. Existing power lines to be raised prior to any OLE wiring activities in this area.
Cii. Unconfirmed buried service may be present in this area.
Ciii. Cable trough route present on Up Main side from strucutre MLN/140/590 to MLN/141/150.
Civ. OLE adjacent to (and above) proposed signal.
Cv. Existing signal gantry to be removed prior to OLE wiring.
Cvi. OLE structure in close proximity to Drainage Duct/Catch pit.
Cvii. Possibility of operational E10K cables running adjacent to proposed foundation locations. Risk of damage due to vibration.
Cviii. Risk of proposed foundation being within 15m of Demolished overbridge.
Cix. OLE structure in proximity to drain route.
Cx. OLE structure close proximity to redundant services' foundation.
Cxi. Presence of cast iron syphon at 141.086km.
Environmental
Ei. Within 20m of a potential badger Set - Contractor to assess the risk to badgers.
Eii. Within 30m of a potential otter habitat - Contractor to assess the risk to otters.
Eiii. Within 20m of a potential bat roost - Contractor to assess the risk to bats.
Eiv. Light frame building within 15m of Foundation.

Figure 331: Warning triangles denoting hazards on a layout plan

17.13. Programme

A robust project programme is an essential precursor to beginning the design phase. This should be developed only once the project scope has been defined, to avoid rework and abortive costs. The programme should be agreed with all stakeholders, and progress of design and construction should then be tracked against the programme. Contractual arrangements should be taken into account when writing the programme, since these can influence the time taken to complete elements of the work.

It is essential that the programme is driven by a realistic expectation of the rate of design and construction outputs. Entry Into Service (section 20.8) dates should be driven by available output, and not the other way around.

17.13.1. Work Breakdown Structure

A *Work Breakdown Structure* (WBS) should be established and agreed, organising all of the activities that make up the programme. Organisational and personal accountability for each element of the WBS must be clearly defined; this allows the project planner to build a clear framework for agreeing and maintaining the programme. WBS elements are often embedded in design and construction contracts.

WBS activities are then be added to the programme to define the elements of work to be completed. It is important to consider and document realistic project working times; the availability of resources - people, plant and materials - is a key constraint on the programme, and these must be taken into account. Procurement

durations (section 19.2.4) for items with *long lead times*[201] should be obtained from suppliers. Construction durations (section 19) will be dependent on track access arrangements, labour resources and plant.

17.13.2. Programme Logic

The *programme logic* - that is, the dependencies between the start and end of individual activities - is equally important to get right, since slippage of one activity will have consequences for multiple later steps. Electrification projects are multidisciplinary, and logic between disciplines must be included in the programme.

Depending on the contracting strategy there may be a requirement for programme integration between multiple parties (client and contractors), which should be considered when producing the baseline programme. Interfaces between parties should be defined and managed as part of the programme.

It is important to include gaps between the completion of one construction activity and the beginning of the next; this time is used for completion of quality assurance checks, and failure to allow time will lead to quality problems that will eventually delay entry into service.

17.13.3. Assumptions and Risks

All key assumptions and risks should be recorded in an assumptions document, sometimes referred to as a *basis of schedule* or *programme narrative*. This document is updated throughout the project life cycle. Each assumption and risk should be assigned an owner, who will manage that risk to conclusion. While often not a contractual requirement, it is an essential tool for managing change during the programme.

All activities, durations, programme logic, interfaces, assumptions and risks should be agreed with the project engineers, taking into account previous experience of electrification projects. All parties should formally accept the programme before work starts.

17.13.4. Measuring Progress

As well as programme updates, design and construction metrics can be a helpful way to communicate progress against the baseline programme. However it is important to remember that individual installed items are components of an overall railway system, and so metrics work only if chosen wisely as meaningful steps along the way to entry into service. Metrics drive designer and installer behaviour that can be hard to change, especially if embedded in contracts. For instance, measuring foundation installation (section 19.4) across a project is counter-productive, since it is possible to achieve 95% completion and still have a pile missing in every construction unit, thus preventing any wiring (section 19.12) taking place. A more meaningful metric is to treat completion of all foundations in a construction unit as a single target.

It is equally important to measure metrics accurately; for instance a foundation is not complete until the holding down bolts (section 11.11) have been installed and the as-fitted location confirmed as within tolerance.

Carefully-chosen and measured metrics are however an essential project tool, allowing progress to be compared to the plan, giving the team confidence that works are on target and highlighting where early intervention and mitigation is required. Metrics should be clearly documented and communicated, and the project should clearly define how the individual targets come together to allow testing and commissioning (section 20) and entry into service to be completed.

[201] Typical long lead items include cantilevers, insulators, registration arms, section insulators, neutral sections, isolators, bridge arms and tensioning devices.

A reporting cycle - usually monthly or four-weekly - should be agreed and implemented before work commences.

17.13.5. Change Management

Once an agreed set of requirements (section 17.2) and programme is in place, a process for change management should be implemented on the project. Change is inevitable on any large programme of work, but must be undertaken in a structured and informed way, since poor change management is implicated in most project failures. Determining which changes are acceptable and which are not is a matter for the individual project, but each change must be rapidly identified and scoped, and an impact attached to it in terms of:

- Cost;
- Programme time;
- Safety;
- Quality of output.

The change should then be reviewed by the project team, and budgets and programme adjusted to take account of the new reality. As a general rule, changes should be avoided to a section of OLE which has entered the construction phase as this is extremely disruptive to the process set out in section 19. Instead the change should be undertaken in a separate sequence once construction activities are complete.

18. The Design Phase

The design of OLE is subject to a strict process designed to ensure that designs are safe, robust and meet the performance criteria. This section focuses on the general principals, with examples of UK practise used to demonstrate the process.

As with the planning phase (section 17), the design phase involves all railway disciplines and cannot simply be viewed as delivery of OLE design. A typical electrification scheme will involve civil engineers (bridge attachments, canopy cutbacks, substation compounds), geotechnical engineers (foundation designs), signalling engineers (signal sighting, head changes, structure modifications, immunisation), track engineers (track lowers at bridges), telecoms engineers (immunisation) and electrical engineers (earthing and bonding) as well as OLE and P&D engineers.

The general sequence for design is as follows:

1. Gather existing asset data;
2. Undertake surveys;
3. Complete outline design;
4. Undertake Interdisciplinary Design Check (IDC);
5. Repeat steps 1 to 4 for detailed design;
6. Produce *Approved For Construction* (AFC) drawings.

The reality is far more complex than this simplistic list would suggest; there are multiple dependencies between different elements of the design - for instance, between the OLE design at a location and the design of a reconstructed bridge carrying OLE attachments; and between design, procurement and construction. It is therefore essential that the design is carried out against a robust project programme (section 17.13).

The following sections focus on new electrification at 25kV AC on an existing mainline railway, but many of the activities described are also needed for the other types of project.

18.1. Surveying

It is essential that all new electrification or modification to existing electrification is based on an accurate and recent survey. It is not sufficient to rely on existing record drawings, as these are not always kept up to date. The range and extent of the surveys required depends on the nature and extent of the work to take place. The expense and time needed for surveys means it is essential to coordinate the requirements of the electrification surveys with those of other disciplines to ensure an integrated survey strategy, and to reuse existing recent surveys where available.

Figure 332: Height and stagger survey with non-contact gauge

18.1.1. Height and Stagger Survey

For modifications to existing OLE, it is essential to understand the current geometry and configuration of the existing OLE. This is traditionally captured during a *height and stagger survey*, where a small survey team use a *height and stagger gauge* to capture basic OLE geometry at each support and/or registration point, and often at midspan locations as well.

The gauge typically comprises a laser distometer held in a transverse sliding mount with a horizontal ruled scale, which in turn sits on the running rails of the track to be measured. The laser dot is placed on the point of interest; the height is measured using the distometer, and stagger is measured using the ruled scale. Track cant, mast offset from track[202] and span lengths are often measured at the same time.

The height and stagger survey should also capture high quality photo images of the support and registration arrangements, to allow the designer to determine the available adjustment in the equipment. Any other relevant information which could affect the design, such as splice locations (section 11.17.1), damaged equipment or fixing details should also be recorded during the survey.

Traditional height and stagger surveys are time-consuming and require safe track access, and so they are increasingly being deprecated in favour of point cloud surveys (section 18.1.2), which can safely gather much more information in a shorter period of time. An alternative to this for simple locations is to use the output from train-mounted OLE monitoring (section 22.2) to provide recent OLE geometry data.

18.1.2. Geospatial Surveys

Geospatial surveys provide a much more complete survey of a section of railway than the height and stagger survey can, providing vital context and spatial relationships with other infrastructure, as well as a 3D output that can form the basis of a multi-disciplinary design model.

The traditional technique for these surveys is to use a tripod-mounted *total station theodolite* to gather angle and distance measurements to key points. These are then geo-referenced to the required *geographic grid* for the project using the *Global Navigation Satellite System* (GNSS) receiver on the total station.

This approach provides high accuracy, and is often necessary to collect specific track data such as toes of points; but it is still a relatively time-consuming way to collect the many points needed for a complete OLE system and the surrounding infrastructure.

For this reason projects are increasingly using *3D point cloud scanning* techniques to gather survey data for railway projects. The configuration of the surveying equipment varies, but all work on the same basis; a *Light Detection And Ranging* (LiDAR) scanner uses a rapidly-sweeping laser to gather angle, distance and colour data across the entire field of view. The data is then georeferenced in the same way as traditional topographical surveys.

The advantage of a 3D point cloud scan is its ability to gather detailed information on a whole section of railway in a very short period of time, often without the need to place people or equipment on the live railway. LiDAR scanners can be used in a number of different ways, including:

- Lineside scanning using a tripod-mounted 360° scanner;
- Drone-mounted scanning;

[202] In the UK this dimension is measured as *Running Edge to Face Of Steel* (REFOS).

- Train-mounted scanning;
- Aircraft-mounted scanning.

Each technique offers different advantages, disadvantages and accuracy. The accuracies quoted below are based on best-in-class methods, and highly dependent on the detail of the survey equipment and methodology.

Technique	Advantages	Disadvantages	Accuracy	Suitability
Lineside tripod	Cost-effective for small sections; easy to eliminate shadows	Inefficient for longer sections	High	All design stages
Drone mounted	Cost-effective; can survey longer sections quickly	Cannot eliminate shadows under structures; vegetation can mask ground levels unless clearance takes place; legal limitations on overflying a live railway	Medium to High	Outline design only
Aircraft mounted	Fastest way to capture long lengths of railway; can capture surrounding terrain and buildings	Expensive; cannot eliminate shadows under structures; vegetation can mask ground levels; minimum height restrictions on overflying a live railway	Low	Feasibility design only
Train mounted	Can capture long lengths of railway quickly	Requires planning and coordination of train availability and paths; not cost-effective for smaller projects; vegetation can mask ground levels	High (with sufficient passes)	All design stages

Figure 333: (l-r) Lineside LiDAR scanner, in use scanning an OLE structure

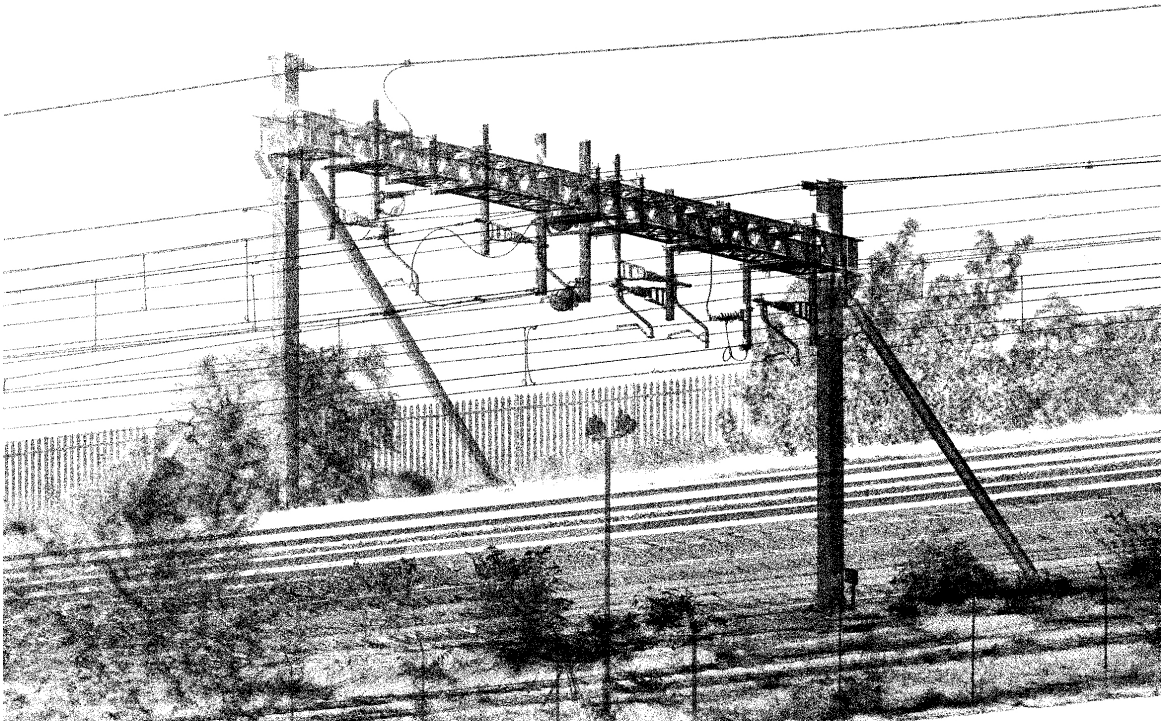


Figure 334: Point cloud scan output from a 1½ hour lineside LiDAR scan of the structure in figure 333

18.1.3. Geotechnical Surveys

The geotechnical ground characteristics play a large part in determining the correct OLE foundation to use (section 11.11), and failure to correctly understand the ground conditions will have adverse impacts on the rate of installation (section 19.4), as well as the foundation's ability to withstand the loads imposed on it (section 11.9). The ground conditions are a direct input to the foundation design (section 18.4.4).

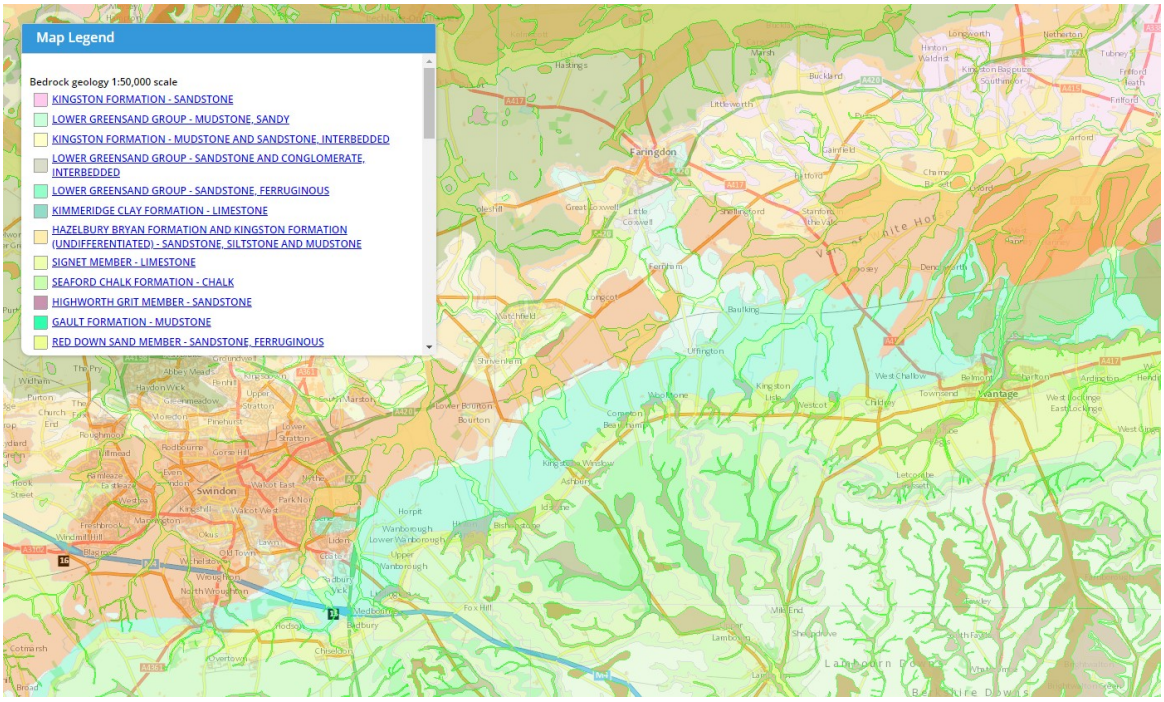

Map Legend
Bedrock geology 1:50,000 scale
KINGSTON FORMATION - SANDSTONE
LOWER GREENSAND GROUP - MUDSTONE, SANDY
KINGSTON FORMATION - MUDSTONE AND SANDSTONE, INTERBEDDED
LOWER GREENSAND GROUP - SANDSTONE AND CONGLOMERATE, INTERBEDDED
LOWER GREENSAND GROUP - SANDSTONE, FERRUGINOUS
KIMMERIDGE CLAY FORMATION - LIMESTONE
HAZELBURY BRYAN FORMATION AND KINGSTON FORMATION (UNDIFFERENTIATED) - SANDSTONE, SILTSTONE AND MUDSTONE
SIGNET MEMBER - LIMESTONE
SEAFORD CHALK FORMATION - CHALK
HIGHWORTH GRIT MEMBER - SANDSTONE
GAULT FORMATION - MUDSTONE
RED DOWN SAND MEMBER - SANDSTONE, FERRUGINOUS
Faringdon
Swindon

Figure 335: Bedrock and surface geology for a region of the UK[203]

[203] British Geological Survey Materials; UKRI; 2020.

The geotechnical investigation starts with a desktop study which reviews existing information. Geological survey maps are typically reviewed to determine the superficial and bedrock geology across the site. Information on mining risks, any historical boreholes, hydrogeology, and the potential presence of contaminated land is also reviewed.

These maps are not sufficiently granular to determine the ground conditions at a specific OLE structure location, and they can only provide information on natural ground conditions - whereas railways are constructed on a mix of natural ground (for flat and cutting sections) and *made ground* (for embankments).

For this reason, the desktop study is followed by a geotechnical *Ground Investigation* (GI). Exploratory hole locations are planned along the route, using information from the desktop study helping to identify appropriate hole locations. Borehole spacings depend on a number of factors, including ground conditions, the availability of historical borehole information, and the presence of historical mining. Typical borehole spacings are between 150m and 500m. It is essential to carry out appropriate GI along a route to be electrified, to derisk the construction phase (section 19.4) as much as possible.

A range of different ground investigation methods are available, depending on the information needed. A selection of which are summarised in the table below.

Ground Investigation Method	Description	Information Provided
Windowless Sampling	Used to bore through soft, shallow soils. In-situ testing such as a *Standard Penetration Test* (SPT), *Cone Penetration Test* (CPT) or dynamic probe testing can also be undertaken. Borehole installations such as water or gas monitoring wells and piezometers can also be included.	Suited to exploratory holes 5-8m deep. Resulting borehole log shows ground characteristics (superficial and/or bedrock geology, thickness of different units, water level).
Cable percussion (shell and auger) drilling	Used to bore through harder strata. Boreholes can be drilled at a variety of diameters (such as 150mm, 200mm, 300mm). As above, in-situ testing can also be undertaken.	Suited to deeper exploratory holes, up to 50m; depths of 10-12m are usually sufficient for OLE foundations. Borehole logs can also be produced.
Standard Penetration Testing (SPT)	An in-situ test giving information on soil strength. Uses a standard tube size which is driven 150 mm into the ground; the number of blows required for the tube to penetrate each 150 mm (up to a depth of 450 mm)	The blow count can be correlated to different sediment types and indicates the hardness or otherwise of the sediment.
Dynamic Probing	A fixed cone is driven into the ground using a high frequency hammer, and blows per 100mm are recorded.	Gives information on the strength of the ground material, in a similar way to SPT testing.

18.1.4. Buried Services

Wherever new OLE structures are to be installed, it is essential to the safety and continued performance of the railway that the location of all buried services is accurately known. This can be very challenging on older railways, where historical records may be poor, and cables may have subsequently moved under the action of

track maintenance. Railway corridors often carry a wide variety of services, crossing over, under or running alongside the track including:

- Railway signalling and telecoms cables;
- Third party telecoms cables;
- HV and LV power cables;
- Water and gas;
- Culverts and drains.

The process usually starts with the construction of a *buried services model* based on a comprehensive search of the services records for the route. This will generally be a low-accuracy CAD model, since the underlying records will have some uncertainty.

The model is then used to avoid services during the design process. Where an OLE structure must be placed in close proximity to the service, additional surveys should be undertaken to confirm an accurate position.

In recent years it has become common practice in the UK to dig a one metre deep *trial hole* at every proposed foundation location to confirm the absence of services. This practice was introduced by the Great Western Electrification Programme (section 8.6) to mitigate the local practice of burying signalling cables directly into the lineside ballast. However the practice has two major shortcomings:

- It removes up to 1m of effective depth (section 18.4.4) from every foundation location, necessitating a deeper foundation to compensate;
- It introduces an additional time-consuming step in the design process, as trial holes must be dug in between layout plan design (section 18.4.1) and cross section design (section 18.4.3).

Taken across a whole route this is an expensive process. It has also been used as a way of checking local ground conditions, but a well-specified borehole strategy (section 18.1.3) is sufficient to derisk ground conditions without the need for trial holes.

A number of more effective alternatives to trial holes exist, such as more effective use of local maintainer knowledge and record drawings, slit trenching, *tag and trace* identification of cables, or scanning with a *Cable Avoidance Tool* (CAT)[204].

18.1.5. Environmental Survey

Environmental surveys are necessary to determine what environmental constraints (section 17.11) exist within the boundaries of the project; in particular, the ecology of the location (section 17.11.2) must be understood, and this usually necessitates an ecology survey to confirm the presence of protected species and habitats.

18.1.6. Windspeed Survey

An accurate assessment of the maximum windspeeds likely to be experienced by the OLE is essential to correctly determine the wind loads on the structures (section 11.9.1) and the blowoff experienced by the contact wire (section 11.13.2).

Windspeed assessments in the UK were traditionally undertaken using a simple on-site assessment of topographical and height factors, and applying these factors as modifiers to a base windspeed derived from a

[204] Use of a CAT is not sufficient in itself, as the tool is not capable of detecting all services, but it can be used as part of a wider cable detection strategy.

map similar to that in section 11.9.1[205].

This process was subsequently replaced with one derived from the Eurocodes[206]. This approach is much more complex to apply, and more suited to building design, involving as it does the assessment of *Orography Factors*[207], distance to coastline and other parameters. While this approach does have the advantage of not requiring a site survey, many designers are adopting a simplified version of the process more appropriate to small-scale structures such as OLE masts.

Regardless of the process, the output is a set of design windspeeds and/or wind pressures, which vary along the route as the topography changes. These are used in subsequent design calculations to ensure that the resulting system is reliable and safe.

18.2. Power and Distribution Design

The P&D design forms the interface between the traction power system and the OLE system (section 17.4), and details the location and electrical functionality of the railway power system, as well as its monitoring, control and operation. The design is developed from the MFD (section 17.4) and section diagram (section 17.6.1), and interfaces with the OLE layout plans (section 18.4.1 and switching cross sections (section 18.4.3)).

18.2.1. Substation Single Line Diagram

The *substation Single Line Diagram* (SLD) details the electrical relationships, layout and connections between the primary electrical plant at each substation, including connections to both the traction power system and the OLE. It also specifies the unique naming of each item of equipment, an essential safety prerequisite for use in safety-critical communication.

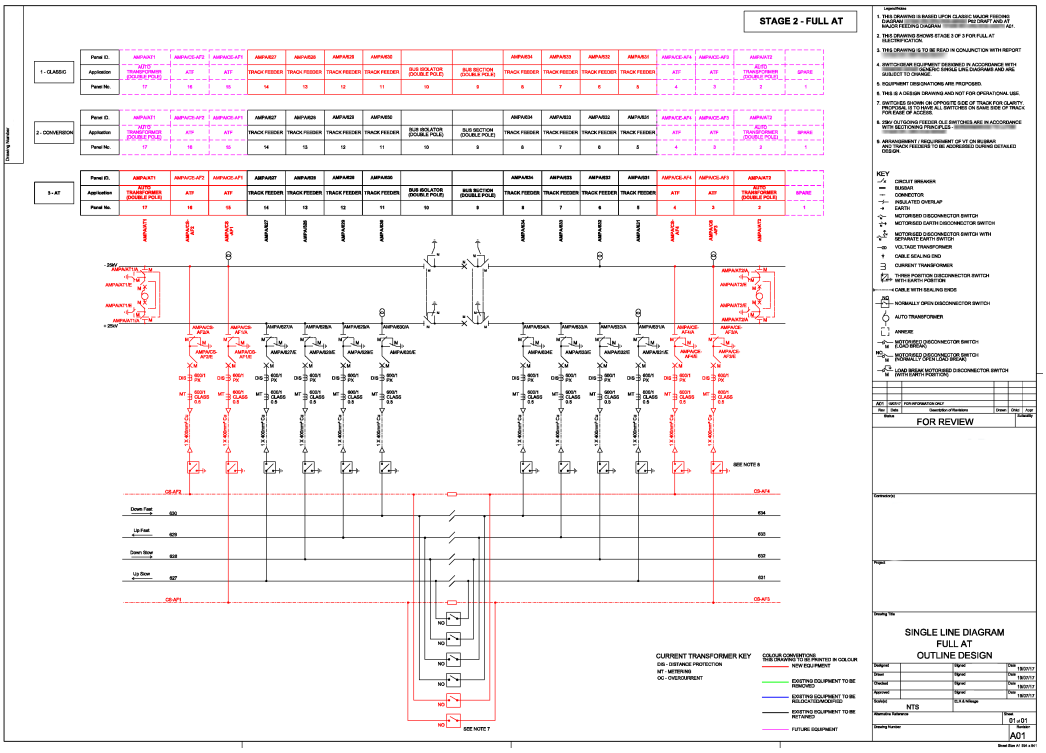


Figure 336: Substation Single Line Diagram for a TSC with facility for future conversion to SATS

[205] ECP34 "Wind Loading on Overhead Line Equipment and Structures"; Issue 3, April 1980.

[206] NR/L2/CIV/072 "Wind Loading of Overhead Line Equipment and Structures"; Issue 2, December 2019.

[207] Orography is the study of the speeding up of wind as it flows up slopes.

18.2.2. Substation Protection Block Diagram

The *protection block diagram* develops the SLD by adding detail that defines the interaction between the electrical protection (section 10.7.1), circuit breakers (section 10.2.7), current transformers and voltage transformers. This is especially important for feeding sites which have a critical electrical protection interface with the NGC/DNO. The rating and class of CTs and VTs at these sites must be agreed between the railway infrastructure manager and the NGC/DNO.

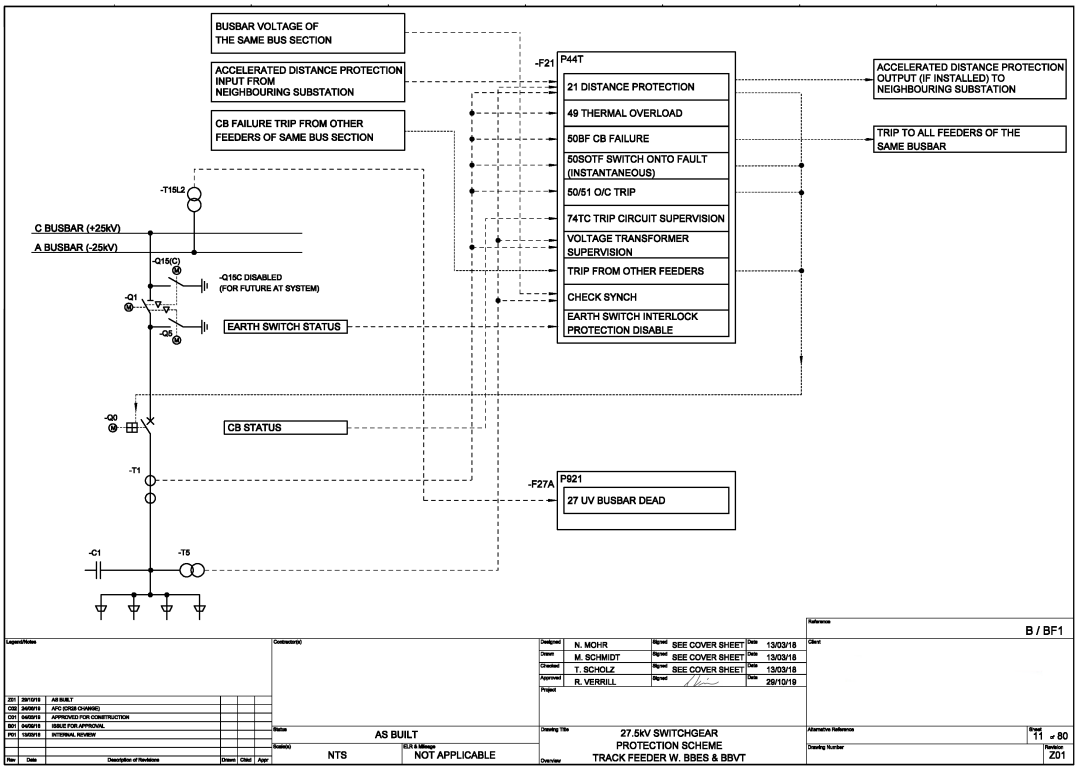


Figure 337: Substation Protection Block Diagram

18.2.3. Substation Schematic

The *substation schematic* is an electrical schematic of a substation site, showing the power and distribution circuit from the incoming grid transformer (section 10.2.2) (if provided) through to the outgoing connections to the OLE. Historically both AC and DC circuitry were shown, but switchgear suppliers now produce schematics split by function. The schematic shows the control and protection functionality of the protection relays (section 10.7.1), circuit breakers (section 10.2.7), disconnectors, VTs and CTs (section 10.7.2).

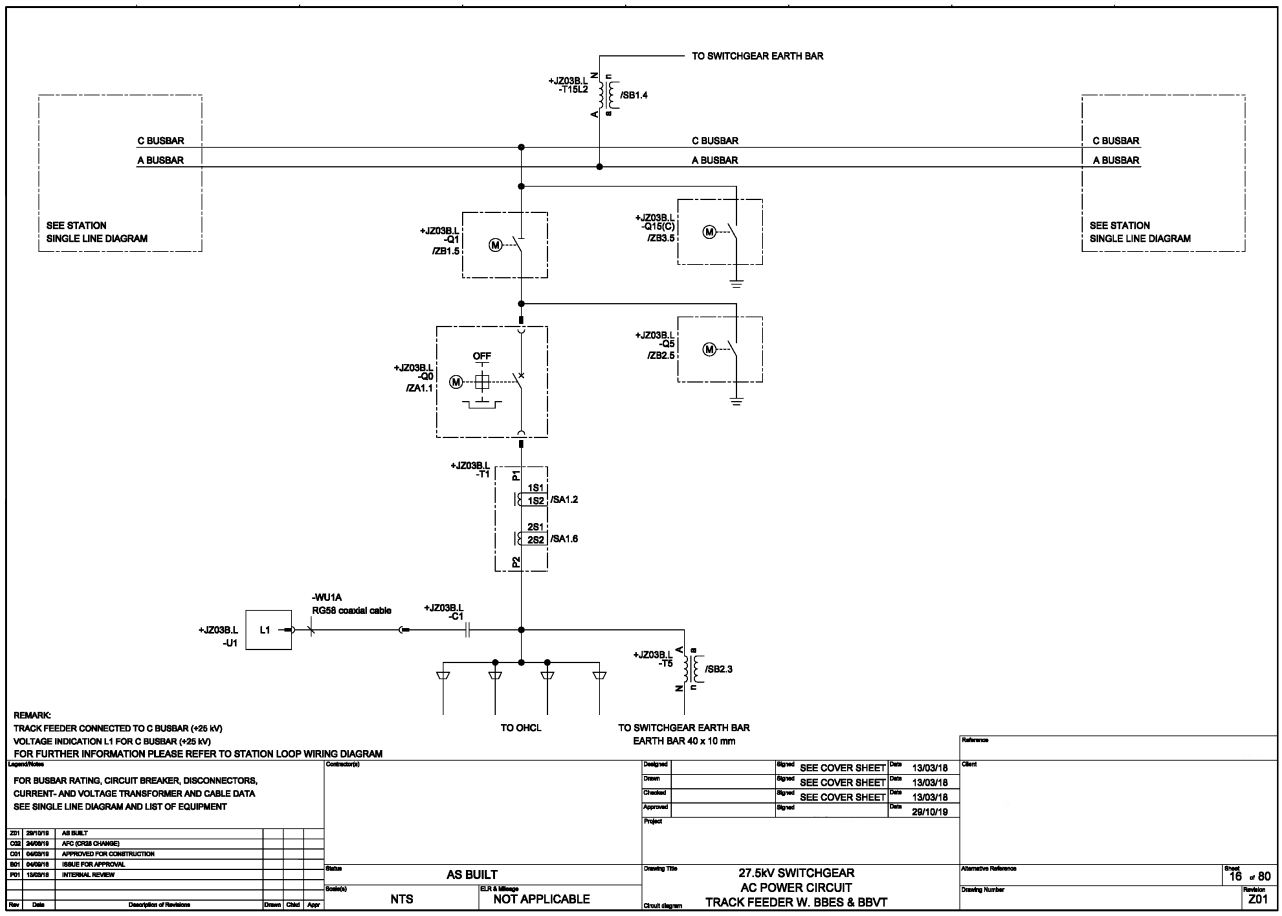


Figure 338: Substation AC Schematic

18.2.4. Substation Layout Design

The *substation layout design* shows the detail of the physical equipment at a substation, based on the SLD and the agreed technical solutions such as AIS or GIS (section 17.5). It shows equipment bases, trough routes, access roads, fencing and building layouts, and includes interface routes and connections to the NGC/DNO and the OLE as appropriate. The output of this process is a series of site layout drawings for each substation site, which in turn enables the civils drawings for the site to be developed.

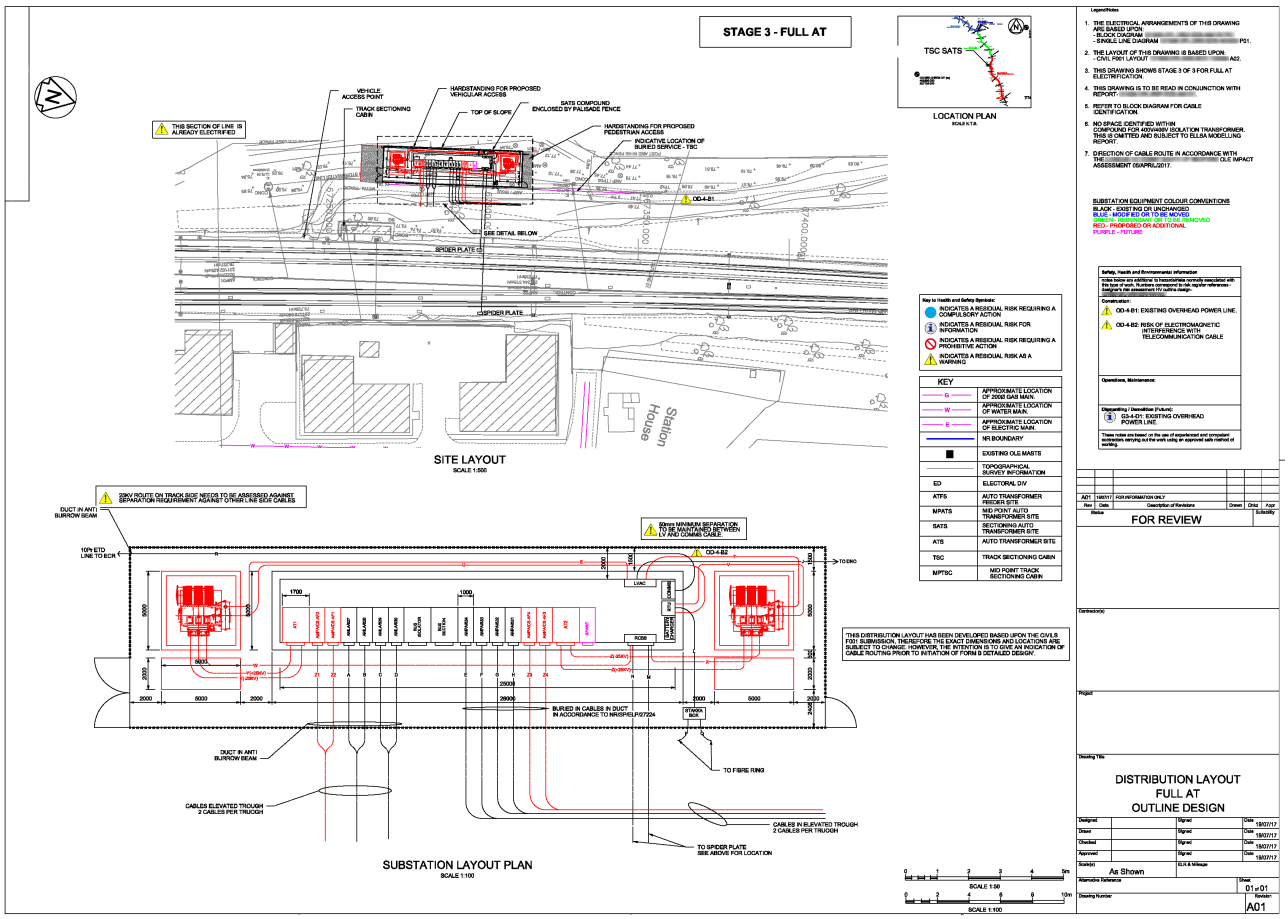


Figure 339: Substation Layout for a TSC with facility for future conversion to SATS

18.2.5. Substation Ancillary Design

A number of supplementary equipment designs are required at each substation location. These include:

- Battery charger (section 10.2.8);
- SCADA RTU (section 10.7);
- Telecoms design;
- LV supply from local DNO (section 10.2.5), including isolation transformer (section 10.2.4) if required.

Each of these will be provided with its own electrical schematics and equipment layout drawings as necessary.

18.2.6. SCADA Design

The SCADA (section 10.7) design is based on the section diagram (section 17.6.1) and substation SLD (section 18.2.1), and depicts the SCADA or control system operated by the ECO. It shows all of the controllable devices within the electrification system, and sometimes the manually controlled devices under the control of the ECO. The resulting drawing can be challenging to develop - especially for auto transformer (section 10.4.3) systems - since it must show all devices within the geographical scope, while remaining easy to read and understand.

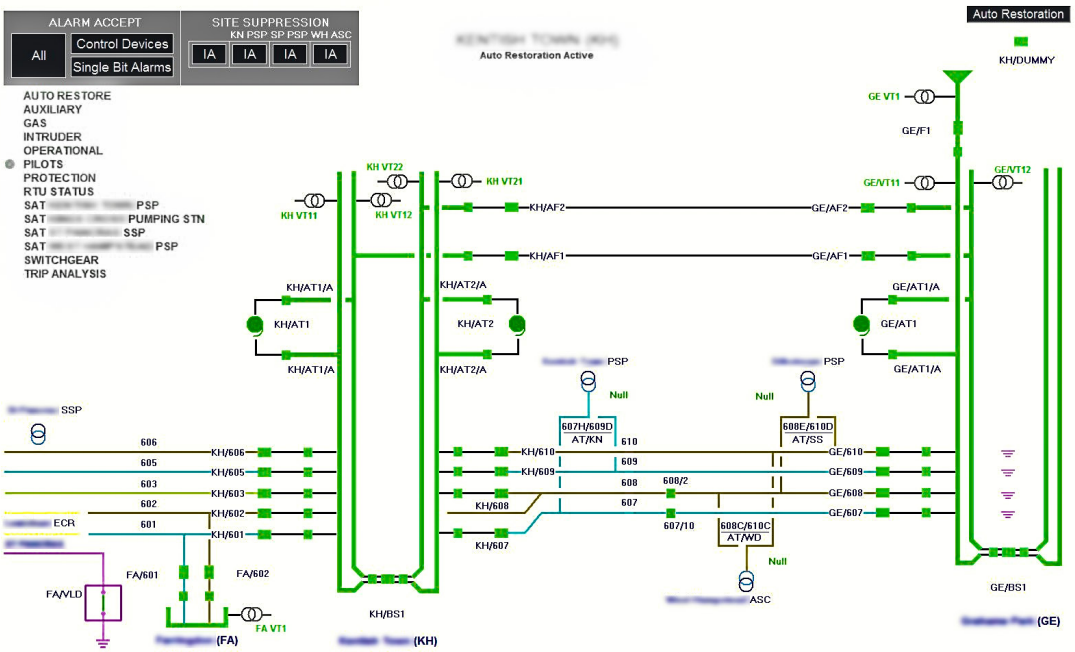


Figure 340: Typical SCADA schematic for mainline railway

18.3. Enabling Designs

Enabling design describes any design which modifies a non-electrification asset to permit electrification of a route to proceed, and section 17.7 details the assets that typically need modification. It is beyond the scope of this book to detail the design processes for these asset modifications, but it is essential that these designs are planned in good time, since the completion of enabling works construction is a precursor to many of the OLE construction activities (section 19).

18.4. OLE Allocation Design

OLE *Allocation Design* - also known as *Application Design* - is the process of applying the design rules, components and assemblies set out in the System Design (section 17.9.1) and Basic Design (section 17.9.2) to a location or route, and this process is at the core of any new electrification design. The process will drive, define and interface with all the modifications to existing railway assets (section 17.7) which are necessary to permit the electrification construction phase (section 19) to proceed. For this reason it is essential to carefully plan the sequencing of the Allocation Design process and the related infrastructure designs; as a broad principle, the OLE design should be sufficiently advanced to fully define the requirements of the enabling designs, before those enabling designs are completed. Failure to do so will inevitably result in rework of the supporting design - or worse, rework to the construction - once the OLE design is fully understood.

OLE designs for specific locations are presented in a standardised manner by a series of drawings, schedules and documents. This is to ensure that the details are easily understood by any competent person, and that no ambiguity can be present in the design. It should be noted that any proposed alteration to OLE will affect some or all of these drawings. Additionally, changes to other railway systems will often have an impact on the OLE drawings.

In the UK no written standard for drawing formats exists; however there are several examples of industry best practice in circulation. Detail of drawing formats tend to be agreed on a project by project basis, with specific details depending on client, contractor and designer preferences.

18.4.1. OLE Layout Design

Layout Design takes place against an agreed Section Diagram (section 17.6.1), Wire Run Diagram (section 17.10.1), and track geometry (section 17.8), and is the process of setting out:

- OLE structure locations and types (section 11.10);
- Wire run positions and anchoring (section 11.4);
- Overlap positions and configurations;
- Junction wiring configurations (section 11.5);
- OLE geometry (sections 11.13.1 and 11.13.2);
- Overbridge, level crossing (section 16.11) and station (section 16.10) wiring configurations;
- Ancillary wiring (section 11.16.5) configurations and geometry;
- Switching locations and configurations (section 11.7);
- Location of DEPs (section 10.12.1);
- Any alterations to existing OLE, track and/or signals;
- Along-track positions of track features (such as turnouts) and signals.

The process includes a full assessment of signal sight lines (section 16.7.1) to ensure that the new or modified OLE will not infringe on minimum sighting distances to any signal.

The output of this process is one or more *OLE layout plans* - this is the first drawing in the electrification hierarchy to show any geometric detail of the OLE. It is typically drawn at 1:500 for complex areas, and smaller scales for plain line areas, and shows OLE structures, wire runs, RCs, ATFs, earth wires, overlaps, SIs, track curvature, span lengths, height and stagger, jumpers and other plan information.

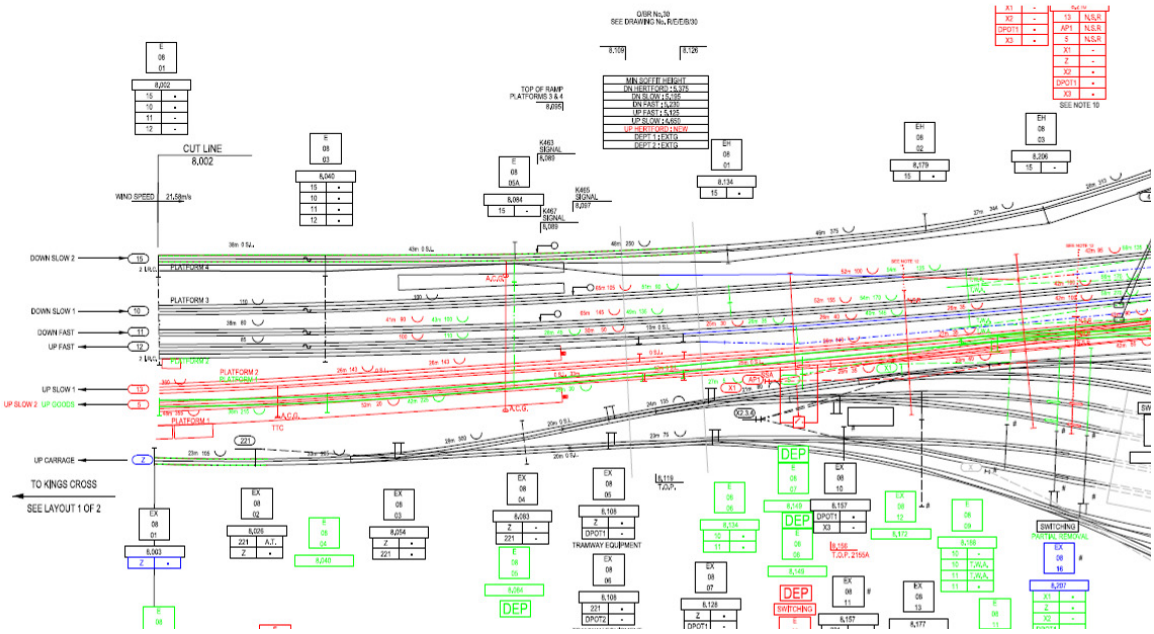


Figure 341: Typical layout plan detail

18.4.2. Site Walkout

It is essential to subject the initial layout plan to a *site walkout* carried out jointly between the OLE, geotechnical and civil designers, and the installer. This allows the layout design to be checked for construction practicality. The location of each structure will be checked, coordinates confirmed and the position of any local cable routes or other obstacles recorded. Where a problem is found, an alternative structure location will be identified by the group.

The layout plan can only be finalised once this process is completed, and the cross section design and foundation design should not proceed without a completed site walkout.

18.4.3. Cross Section Design

OLE Cross Section Design builds on the layout plan and involves detailing of the individual OLE structures, providing the structure geometry and components necessary for construction. The resulting *OLE cross section* drawing shows detail of a specific cross section across the railway, including one or more OLE structures.

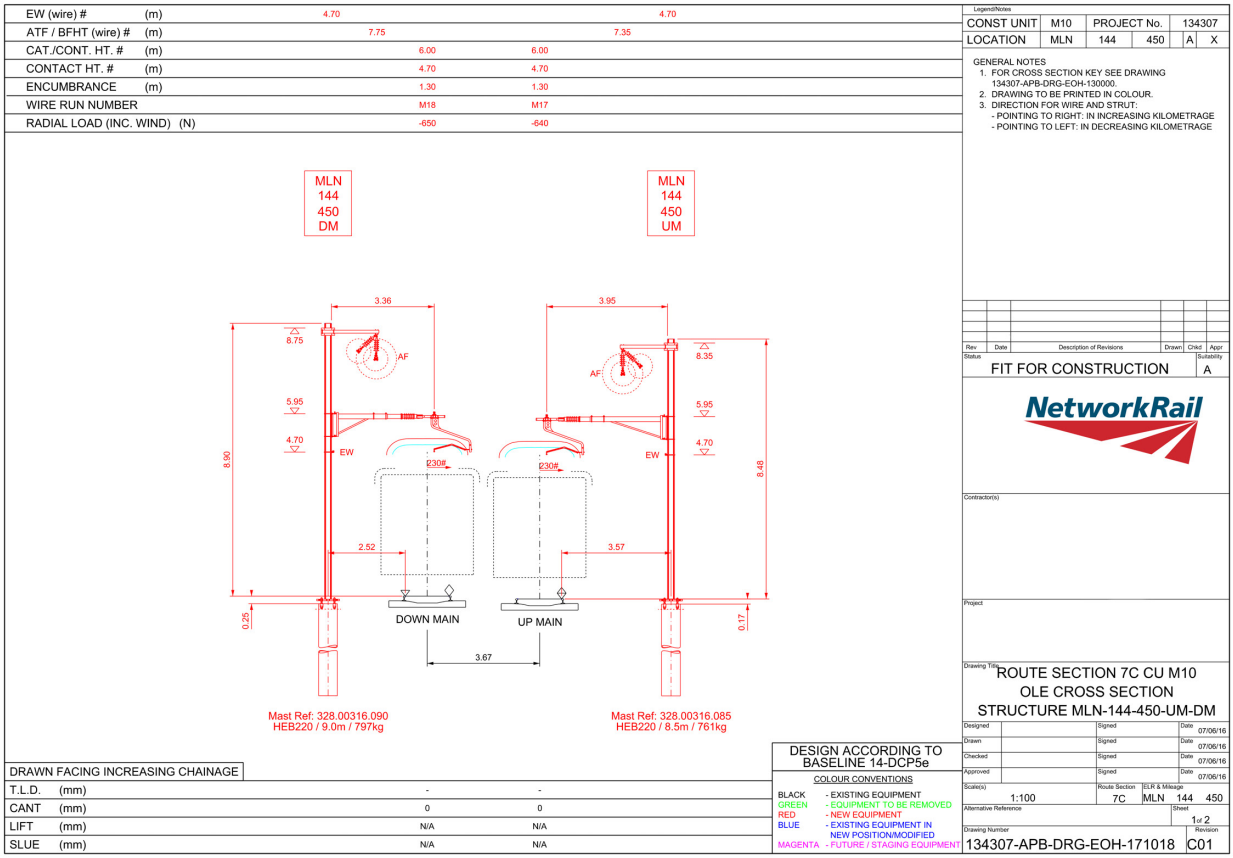


Figure 342: Typical cross section detail - sheet 1

These drawings are typically 1:100 scale and include all the arrangements, dimensions, and assembly part numbers required to build the structure(s). The assembly part numbers are drawn from the basic design range (section 13.1) for the system. The drawing may have more than one sheet - for instance it may be split into support and switching sheets for complex arrangements. The cross section will include appropriate pantograph gauges (section 11.1.2) to confirm that minimum electrical clearances (section 10.8) have been met.

No.	Rev. No	Reference No.	Reference Description	Qty	No Name	M18	M17
1	C01	TBC	M30 Foundation Bolts	12	12		
2	C01	TBC	M30 Foundation Nuts	36	36		
3	C01	TBC	High strength plain washers (EN 14399-6) M30	24	24		
4	C01	328.00308	Washer, on Mast Base Plate, for Bolt M30	24	24		
5	C01	328.00316.085	Wide-Flanged Mast HEB 220, for 6xM30 bolts, on pile Ø610	1	1		
6	C01	328.00316.090	Wide-Flanged Mast HEB 220, for 6xM30 bolts, on pile Ø610	1	1		
7	C01	472.00138.22	Earth Rope Clamp Assembly, for Rope 130-200 mm², for square section 200-260	2	2		
8	C01	442.00135.10	Curved Registration Arm With Ring, Stiffened, With Ring Groove Bar 10° Inclined, Typ 08 - 14	2		1	1
9	C01	431.00025-3	Cable Clamp Assembly, for Cantilever tube ø70	2		1	1
10	C01	371.00282	Ø57/2.9 Registration Tube Reinforced Assembly, for Cantilever tube Ø70, for Single insulator cantilever	2		1	1
11	C01	442.00097	Registration Arm ring fitting, for ø48 Registration tube	2		1	1
12	C01	444.00055	Contact wire swivel clip, groove type for contact wire up to 193 mm²	2		1	1
13	C01	371.00293.09	Cantilever Tube Ø70, for SIC, telescopic	2		1	1
14	C01	372.00474.22	Telescopic Cantilever Frame 1.6, on Mast HEB 200-260, for SIC, telescopic, for Reach 3.1-3.9m	1		1	
15	C01	424.00164	Strut Insulator Strong, 25 kV, Flange 140x140 and Tube fitting Ø70, 12 Sheds	2		1	1
16	C01	372.00476.22	Telescopic Cantilever Frame 2.3, on Mast HEB 200-260, for SIC, telescopic, for Reach 3.8-4.6m	1			1
17	C01	581.00099	Structure Number Plate and Track Marker	2	2		
18	C01	581.00099-1.01	Track Marker Plate	1	1		
19	C01	581.00099-1.02	Track Marker Plate	1	1		
20	C01	392.00031	Stainless Steel Band-It Buckle	6	6		
21	C01	392.00035	Stainless Steel Banding Tape	12	12		
22	C01	451.00287.22	Mounting Bracket Assembly for ATF Suspension 100 x 100 SHS on Mast HEB 200-260	2	2		
23	C01	451.00293	ATF Support Long, for ATF Suspension, in tangent track	2	2		
24	C01	424.00149	Long-Rod Insulator 25kv, Clevis and tongue, 11sheds	2	2		
25	C01	417.00037-1	Clevis and tongue and assembly, clevis hole Ø18 tongue hole Ø22	2	2		
26	C01	433.00236	Double Link	2	2		
27	C01	431.00086	Pivoting Cable Clamp Assembly, for Conductors Ø20-23	2	2		
28	C01	437.00024-1.2	Flexible TF5 Dropper Assemblies	2		1	1

Figure 343: Typical cross section detail - sheet 2 (allocation sheet)

Cross sections should only be produced once the layout plan has been finalised.

18.4.4. Structure Loads and Foundation Design

It is essential to the long-term safety and reliability of an electrified railway that the OLE foundations are capable of withstanding the loads that are applied to it, without risk of significant short- or long-term movement.

Completion of the cross section design (section 18.4.3) enables the actual live and dead loads for the structure to be calculated and combined into a set of load case combinations (section 11.9). An allowance of 10% is typically added to these combinations to negate the need for redesign should the OLE design be adjusted at a later stage. These are fed into the foundation design, along with the grid coordinates[208], geotechnical findings (section 18.1.3), and the required walkout (section 18.4.1) and *Finish Foundation Level* (FFL)[209] based on the ground profile. FFL is typically set at 300mm above the highest point of the surrounding ground.

The selection of foundation types (section 11.11) is a complex topic, driven by a number of construction factors, including:

- Type and condition of natural ground (on level ground and in cuttings) and of earthworks (on embankments);
- Geotechnical considerations such as the presence of a high water table, bedrock, poor embankment stability or soil types that make augering difficult such as gravel or sand;
- Proximity to mining areas;
- Availability of access to the railway;
- Availability of appropriate plant (section 19.4);
- Storage and handling processes (section 19.2.1);

[208] Portal structure foundation locations must be coordinated with the various structure connection tolerances in all three planes.

[209] FFL is the distance in the vertical plane between the top of foundation and the nearest rail.

- Environmental considerations (section 18.1.5);
- Presence of any drainage or buried services (section 18.1.4);
- Local materials availability and cost (section 19.2.4);
- Required production rates;
- National and local preferences.

Foundation selection must take full account of the construction constraints as well as the engineering requirements, and for electrification of operational railways, speed of installation should be prioritised. For instance the maximum length of a single section pile should be treated as a constraint, since jointing of multi-segment piles on site is detrimental to productivity. For these reasons the selection of the appropriate foundation type(s) cannot be made solely by the designer, or indeed the installer; instead the selection should be made with involvement from both parties.

In the UK the output of this process is typically contained in project-wide civils Form 001 and 002 documents. This approach provides a strategy for the detailed design of foundations, and removes the need for basic principles to be re-addressed for every construction unit. The document should include a hierarchy of foundation preference that will be used throughout the project to maximise standardisation of the construction process.

The process of designing OLE foundations also depends on the type of ground at the location and the loads experienced by the structure. In the UK there are three processes available[210], in ascending order of complexity:

1. Standard design with empirical depth setting process;
2. Standard design with Eurocode depth setting process;
3. Bespoke foundation design.

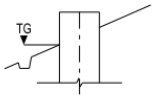
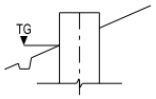
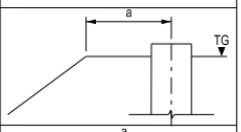
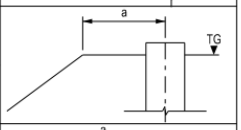
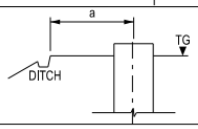
The first option is used wherever ground conditions are expected to be good, and there is no evidence of mining or other earthworks defects. It provides a more efficient design process, and use of the empirical method should be maximised. A standard pile or side-bearing foundation design is selected from the basic design range (section 17.9.2), and the *design depth* is set using standard tables and formulae based on an empirical assessment of the topography of the site and the load bearing capacity of the soil.

In the UK this process is also known as the *ORE method*, and uses formulae derived from physical tests carried out in 1957[211] and updated in 2015[212]. An additional *non-effective depth* is added to the design depth to give the overall foundation length, to account for the loose top section of soil which does not contribute to the load bearing capacity of the ground.

[210] NR/L2/CIV/074 "Design and Installation of Overhead Line Foundations", Issue 01, 2017; Network Rail.

[211] A 1a/RP 1/E "Calculation of Catenary Masts and Foundations", 1957; International Union of Railways (UIC) and Office for Research and Experiments (ORE).

[212] "Assessment of design methods for railway OLE Foundations", W. Powrie, D.J. Richards; 2015; ORE/Network Rail, University of Southampton.

LOCATION CONDITIONS	DIRECTION OF MOMENT	FACTOR F	ACCEPTABLE CONDITIONS	CORRECTIONS	SKETCH
SIDE OF CUTTING	UPHILL	1,37	ALL WITH CORRECTIONS	ADD 0,9 to h	
	DOWNHILL	1,53			
SIDE OF EMBANKMENT	UPHILL	1,37	ALL WITH CORRECTIONS	ADD 0,9 to h	
	DOWNHILL	1,53			
TOP OF CUTTING	UPHILL	1,37	0,9 ≤ a ≤ h	IF a < 0,9, THEN ADD (0,9-a) TO h IF a > h, REGARD AS LEVEL GROUND	
	DOWNHILL	1,53	0,9 ≤ a ≤ 0,7h	IF a < 0,9, THEN ADD (0,9-a) TO h IF a > 0,7h, REGARD AS LEVEL GROUND	
TOP OF EMBANKMENT	UPHILL	1,37	0,9 ≤ a ≤ h	IF a < 0,9, ADD (0,9-a) TO h IF a > h, REGARD AS LEVEL GROUND	
	DOWNHILL	1,53	0,9 ≤ a ≤ 0,7h	IF a < 0,9, ADD (0,9-a) TO h IF a > 0,7h, REGARD AS LEVEL GROUND	
LEVEL GROUND	AWAY FROM TRACK	1,3	a ≥ h	IF a < h, REGARD AS SIDE OF EMBANKMENT	
	TOWARDS TRACK	1,0	a ≥ 0,7h	IF a < 0,7h, REGARD AS SIDE OF EMBANKMENT	

Tubular Steel Pile - 610mm Diameter	
Strength depth D(m)	Level ground moment (kNm)
1.5	25.0
1.6	28.7
1.7	32.7
1.8	36.9
1.9	41.4
2	46.1
2.1	51.0
2.2	56.2
2.3	61.7
2.4	67.3
2.5	73.3
2.6	79.4
2.7	85.8
2.8	92.5
2.9	99.4
3	106.5
3.1	113.9
3.2	121.5
3.3	129.3
3.4	137.4
3.5	145.8
3.6	154.4
3.7	163.2
3.8	172.3
3.9	181.6
4	191.1
4.1	200.9
4.2	211.0
4.3	221.2
4.4	231.8
4.5	242.5
4.6	254.2
4.7	265.6

Figure 344: Typical depth setting ground profile and depth tables for UK standard pile design[213]

Ground conditions that prevent the use of this method include:

- Rock (except chalk);
- Peat (unless GI shows there to be sufficient strength);
- Areas where the earthwork condition is rated as poor, including those where earthworks are undermined by burrowing animals[214];
- Very hard ground (such as surface bedrock);
- Areas where the water table is high;
- Ground which can be affected by dissolution, such as limestone, gypsum and rock salt;
- Areas affected by historical mining;
- Areas of contaminated land.

For these locations, the designer will still use a standard foundation design wherever possible, but the depth will be set using a method derived from the Eurocodes[215] (also known as *EC7*), using geotechnical techniques such as the *Brinch-Hansen method*[216] to determine the likely bearing capacity of the ground, and so determine the design depth.

Most projects also have a small percentage of structures which are not suited to the standard foundation designs. These are typically at locations where unavoidable obstructions exist close to the surface (such as on viaducts), in areas with shallow bedrock, at locations with mine workings close to the surface, or in areas of marshland where no coherent soil exists. These will be the subject of a site-specific foundation design, specific

[213] MS/B98/K05 "Foundation Allocation Schedule - Grabbed and Hand Excavated Side-Bearing Foundations"; R00, 27 March 2017; Network Rail and MS/B80/L00 "Strength Depth Table for Different OLE Foundation Types - Based on ORE-UIC Method"; R00, 27 March 2017; Network Rail.

[214] In the UK, this is defined as *Earthwork Hazard Category* (EHC) D or E, as derived from the *Soil Embankment Hazard Index* (SEHI). EHC indicates the statistical likelyhood of an earthwork failing, and is determined from visual inspections and desk studies. NR/L3/CIV/065 Mod 04 "Definition of Soil Embankment Hazard Index"; Issue 1, September 2017; Network Rail.

[215] BS EN 1997-1:2004+A1:2013 "Eurocode 7 - Geotechnical Design - General Rules"; 31 July 2014; BSI.

[216] More information is available online at bit.ly/3uynQps.

to the location and often taking the form of a gravity pad foundation (section 11.11.5) to resist the overturning moment horizontally rather than vertically.

The resulting *OLE foundation schedule* is a list of foundations, including everything needed for construction. The schedule will typically detail grid coordinates, FFL and walkout, foundation type, orientation and depth, and all other information necessary for construction to begin.

In the UK the foundation schedule is typically delivered as a civils design submission at the same time as the OLE allocation design is submitted for each construction unit.

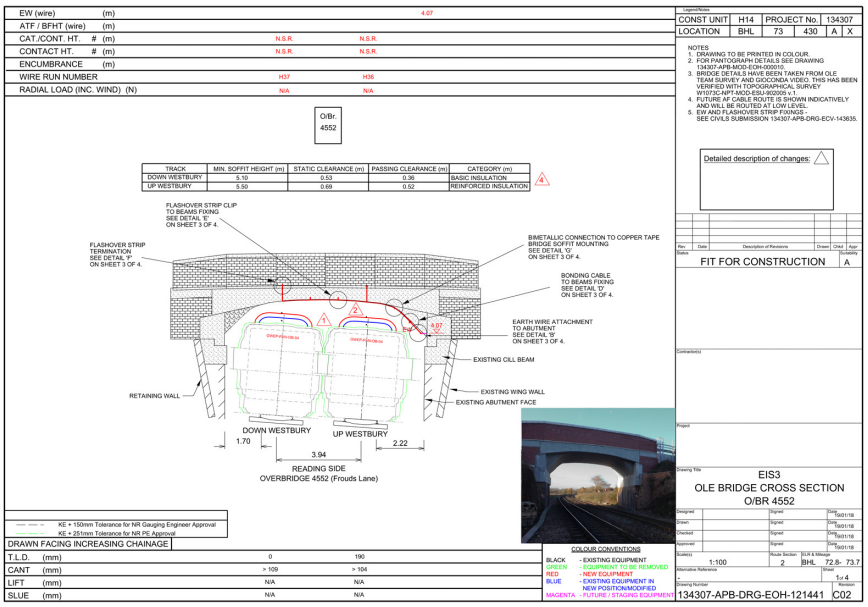
STRUCTURE DETAILS										FOUNDATION DETAILS									
						GPS Location Snake Grid (DESIGN)		Mast / Foundation Interface											
Kilometre	Metre	Track	Structure Type	Mast Section Size	Maximum Across Track/ ^Along Track Moment (Top of foundation) (kNm)	RECOS (m)	X=Easting co-ordinates (centre of foundation) (m)	Y=Northing co-ordinates (centre of foundation) (m)	Orientation	Actual Finish Foundation Level (z-value) (mAOD)	Foundation Type	Foundation Dimension (mm)	Non-effective depth (m)	Foundation length out of ground (m)	Foundation Length including non-effective depth and upstand (m)	Foundation Allocation	No. of Bolts	PPS Pile Cap Allocation	Foundation Design Method
79	659	DF	SSA/STC	308UC	199 ^	3.00	74873.914	72898.965	Perpendicular	28.454	Steel CHS	610 dia.	1.0	0.4	5.9	*B89/B06/159	-	*B83/B08/005	ORE
79	659	UF	SSA/STC	308UC	204 ^	3.00	74884.715	72899.813	Perpendicular	28.661	Steel CHS	610 dia.	1.0	0.4	5.9	*B89/B06/159	-	*B83/B08/005	ORE
79	720	DF	STC	203UC	25 ^	3.40	74867.696	72960.138	Parallel	28.485	Steel CHS	610 dia.	1.0	0.5	3.1	B83/001/231	4	N/A	ORE
79	720	UF	STC	203UC	38	2.90	74878.784	72961.223	Parallel	28.298	Steel CHS	610 dia.	1.0	0.4	3.1	B83/001/231	4	N/A	ORE
79	722	DF	STC	203UC	27 ^	3.40	74867.540	72961.533	Parallel	28.422	Steel CHS	610 dia.	1.0	0.5	3.1	B83/001/231	4	N/A	ORE
79	722	UF	STC	203UC	28 ^	2.90	74878.627	72962.614	Parallel	28.327	Steel CHS	610 dia.	1.0	0.4	3.1	B83/001/231	4	N/A	ORE
79	767	DF	STC	203UC	13 ^	3.50	74861.758	73006.673	Parallel	28.235	Steel CHS	610 dia.	1.0	0.4	2.7	B83/001/227	4	N/A	ORE
79	767	UF	STC	203UC	17	2.80	74872.782	73008.187	Parallel	28.355	Steel CHS	610 dia.	1.0	0.5	2.8	B83/001/228	4	N/A	ORE
79	769	DF	STC	203UC	19	3.50	74861.568	73008.049	Parallel	28.201	Steel CHS	610 dia.	1.0	0.4	2.7	B83/001/227	4	N/A	ORE
79	769	UF	STC	203UC	30	2.80	74872.585	73009.593	Parallel	28.128	Steel CHS	610 dia.	1.0	0.4	2.9	B83/001/229	4	N/A	ORE
79	816	DF	SSA/STC	308UC	122 ^	4.00	74853.996	73054.227	Perpendicular	28.179	Steel CHS	610 dia.	1.0	0.4	5.0	B83/001/250	6	N/A	ORE
79	816	UF	SSA/STC	308UC	185 ^	2.20	74864.874	73056.036	Perpendicular	28.172	Steel CHS	610 dia.	1.0	0.4	5.9	*B89/B06/159	-	*B83/B08/005	ORE
79	878	DF	TTC	380DC	154	3.50	74843.245	73115.403	Parallel	27.896	Steel CHS	610 dia.	1.0	0.4	5.0	B83/001/250	6 #	N/A	ORE
79	925	UF	TTC	380DC	160	3.00	74844.369	73163.979	Parallel	27.966	Steel CHS	610 dia.	1.0	0.4	5.0	B83/001/250	6 #	N/A	ORE
79	974	UF	TTC	380DC	137	2.80	74832.568	73211.728	Parallel	27.827	Steel CHS	610 dia.	1.0	0.4	4.7	B83/001/247	6 #	N/A	ORE
80	24	UF	TTC	380DC	116	3.00	74819.601	73260.238	Parallel	27.892	Steel CHS	610 dia.	1.0	0.3	4.4	B83/001/244	6 #	N/A	ORE
80	69	UF	TTC	380DC	166	4.00	74807.600	73303.805	Parallel	27.988	Steel CHS	610 dia.	1.0	0.5	5.2	*B89/B06/152	-	*B83/B08/002	ORE
80	74	UF	TTC (Tie)	N/A	N/A	4.00	74806.106	73308.576	Parallel	28.055	Steel CHS	610 dia.	1.0	0.4	3.5	B83/001/235	4	N/A	EC7
80	126	DF	TTC	380DC	114	3.10	74778.435	73354.276	Parallel	27.855	Steel CHS	610 dia.	1.0	0.4	4.5	B83/001/245	6 #	N/A	ORE
80	418	DF	TTC	380DC	150	5.50	74658.971	73619.046	Parallel	29.143	Steel CHS	610 dia.	1.0	0.4	4.9	B83/001/249	6 #	N/A	ORE
80	467	DF	Portal	500RHS	42	3.13	74636.902	73663.030	Parallel	29.569	Concrete Augered	1000 dia.	1.0	0.4	3.2	B80/N02/032	6	N/A	EC7
80	467	ES	Portal	500RHS	42	2.98	74658.227	73676.043	Parallel	29.569	Concrete Augered	1000 dia.	1.0	0.4	3.2	B80/N02/032	6	N/A	EC7

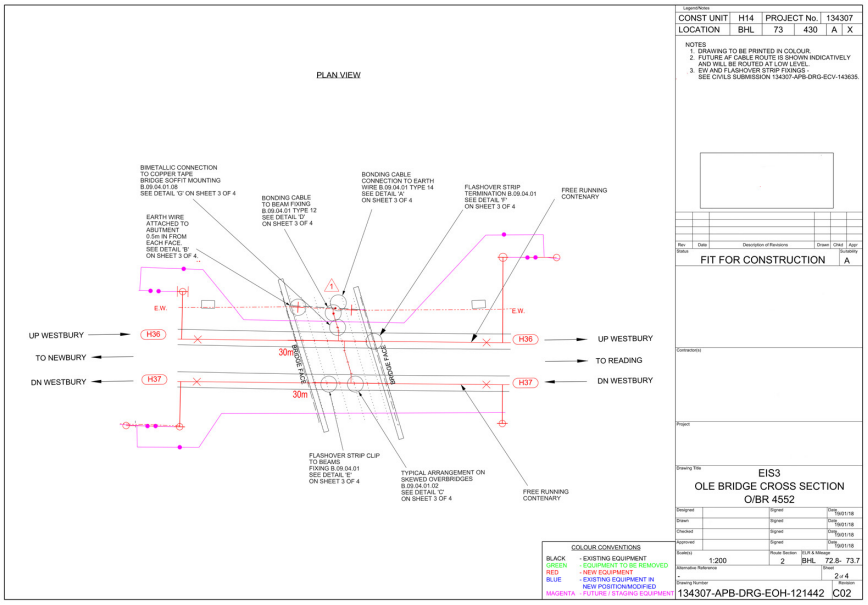
Figure 345: Typical OLE foundation schedule

18.4.5. OLE Bridge Design

OLE Bridge Design is the design of OLE geometry (section 11.13.1) and attachments (section 16.3.1) through an overbridge. This process must be carefully coordinated with the civil engineer, since bridge ownership, form of construction, condition, existing loadings and shape will all influence the final OLE configuration.

The resulting *OLE bridge drawing* is a set of drawing sheets showing the detail of an overbridge with OLE attachments. These are typically comprised of a layout plan (section 18.4.1) extract at a larger scale, and a set of cross sections (section 18.4.3) showing the bridge attachments, and a bonding plan (section 18.4.7) extract. The cross section will also include appropriate pantograph gauges (section 11.1.2).


EW (wire) (m) 4.07
ATF / BFHT (wire) (m)
CAT./CONT. HT. # (m) N.S.R. N.S.R.
CONTACT HT. # (m) N.S.R. N.S.R.
ENCUMBRANCE (m)
WIRE RUN NUMBER H37 H36
RADIAL LOAD (INC. WIND) (N) N/A N/A
O/Br. 4552
TRACK | MIN. SOFFIT HEIGHT (m) | STATIC CLEARANCE (m) | PASSING CLEARANCE (m) | CATEGORY (m)
DOWN WESTBURY | 5.10 | 0.53 | 0.36 | BASIC INSULATION
UP WESTBURY | 5.50 | 0.69 | 0.52 | REINFORCED INSULATION
FLASHOVER STRIP CLIP TO BEAMS FIXING SEE DETAIL 'E' ON SHEET 3 OF 4.
FLASHOVER STRIP TERMINATION SEE DETAIL 'F' ON SHEET 3 OF 4.
BIMETALLIC CONNECTION TO COPPER TAPE BRIDGE SOFFIT MOUNTING SEE DETAIL 'G' ON SHEET 3 OF 4.
BONDING CABLE TO BEAMS FIXING SEE DETAIL 'D' ON SHEET 3 OF 4.
EARTH WIRE ATTACHMENT TO ABUTMENT SEE DETAIL 'B' ON SHEET 3 OF 4.
EXISTING CILL BEAM
EXISTING WING WALL
EXISTING ABUTMENT FACE
RETAINING WALL
DOWN WESTBURY
UP WESTBURY
1.70
3.94
2.22
READING SIDE
OVERBRIDGE 4552 (Frouds Lane)
KE + 150mm Tolerance for NR Gauging Engineer Approval
KE + 251mm Tolerance for NR PE Approval
DRAWN FACING INCREASING CHAINAGE
T.L.D. (mm) 0 190
CANT (mm) > 109 > 104
LIFT (mm) N/A N/A
SLUE (mm) N/A N/A
COLOUR CONVENTIONS
BLACK - EXISTING EQUIPMENT
GREEN - EQUIPMENT TO BE REMOVED
RED - NEW EQUIPMENT
BLUE - EXISTING EQUIPMENT IN NEW POSITION/MODIFIED
MAGENTA - FUTURE / STAGING EQUIPMENT
CONST UNIT H14 PROJECT No. 134307
LOCATION BHL 73 430 A X
NOTES
1. DRAWING TO BE PRINTED IN COLOUR.
2. FOR PANTOGRAPH DETAILS SEE DRAWING 134307-APB-MOD-EOH-000010.
3. BRIDGE DETAILS HAVE BEEN TAKEN FROM OLE TEAM SURVEY AND GIOCONDA VIDEO. THIS HAS BEEN VERIFIED WITH TRADITIONAL SURVEY SEE DRG. 134307-APB-MOD-ESU-000001.
4. FUTURE AF CABLE ROUTE IS SHOWN INDICATIVELY AND WILL BE ROUTED AT LOW LEVEL.
5. EW AND FLASHOVER STRIP FIXINGS - SEE CIVILS SUBMISSION 134307-APB-DRG-ECV-143635.
Detailed description of changes:
FIT FOR CONSTRUCTION A
EIS3
OLE BRIDGE CROSS SECTION
O/BR 4552
1:100 2 BHL 72.8- 73.7
134307-APB-DRG-EOH-121441 C02


PLAN VIEW
BIMETALLIC CONNECTION TO COPPER TAPE BRIDGE SOFFIT MOUNTING B.09.04.01.08 SEE DETAIL 'G' ON SHEET 3 OF 4
BONDING CABLE TO BEAM FIXING B.09.04.01 TYPE 12 SEE DETAIL 'D' ON SHEET 3 OF 4
BONDING CABLE CONNECTION TO EARTH WIRE B.09.04.01 TYPE 14 SEE DETAIL 'A' ON SHEET 3 OF 4
FLASHOVER STRIP TERMINATION B.09.04.01 SEE DETAIL 'F' ON SHEET 3 OF 4
FREE RUNNING CONTENARY
EARTH WIRE ATTACHED TO ABUTMENT 0.5m IN FROM EACH FACE SEE DETAIL 'B' ON SHEET 3 OF 4.
E.W.
UP WESTBURY
TO NEWBURY
DN WESTBURY
H36
H37
30m
BRIDGE No. 4552
TO READING
FLASHOVER STRIP CLIP TO BEAMS FIXING B.09.04.01 SEE DETAIL 'E' ON SHEET 3 OF 4
TYPICAL ARRANGEMENT ON SKEWED OVERBRIDGES B.09.04.01.00 SEE DETAIL 'C' ON SHEET 3 OF 4
CONST UNIT H14 PROJECT No. 134307
LOCATION BHL 73 430 A X
NOTES
1. DRAWING TO BE PRINTED IN COLOUR.
2. FUTURE AF CABLE ROUTE IS SHOWN INDICATIVELY AND WILL BE ROUTED AT LOW LEVEL.
3. EW AND FLASHOVER STRIP FIXINGS - SEE CIVILS SUBMISSION 134307-APB-DRG-ECV-143635.
FIT FOR CONSTRUCTION A
EIS3
OLE BRIDGE CROSS SECTION
O/BR 4552
1:200 2 BHL 72.8- 73.7
134307-APB-DRG-EOH-121442 C02

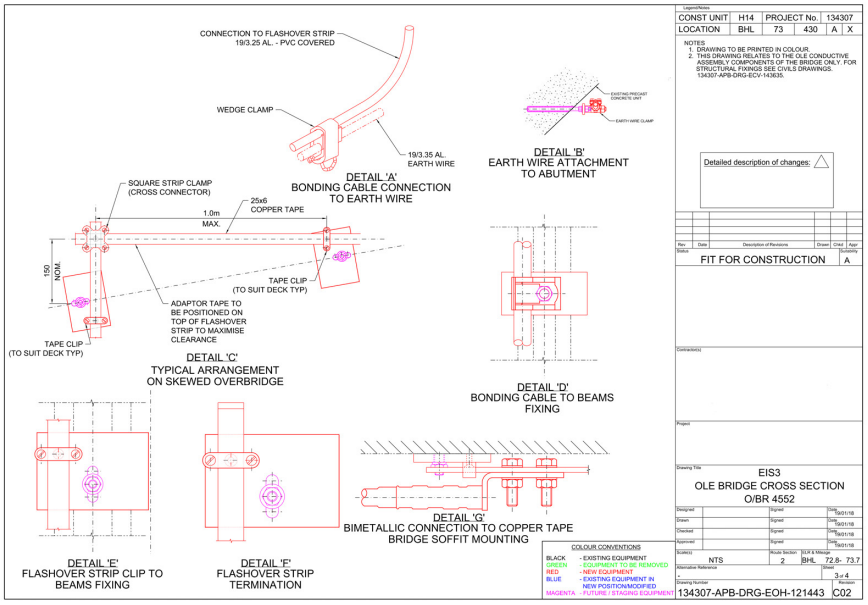

CONNECTION TO FLASHOVER STRIP 19/3.25 AL. - PVC COVERED
WEDGE CLAMP
19/3.35 AL. EARTH WIRE
DETAIL 'A' BONDING CABLE CONNECTION TO EARTH WIRE
DETAIL 'B' EARTH WIRE ATTACHMENT TO ABUTMENT
SQUARE STRIP CLAMP (CROSS CONNECTOR)
25x6 COPPER TAPE
1.0m MAX.
150 NOM.
TAPE CLIP (TO SUIT DECK TYP)
ADAPTOR TAPE TO BE POSITIONED ON TOP OF FLASHOVER STRIP TO MAXIMISE CLEARANCE
DETAIL 'C' TYPICAL ARRANGEMENT ON SKEWED OVERBRIDGE
DETAIL 'D' BONDING CABLE TO BEAMS FIXING
DETAIL 'E' FLASHOVER STRIP CLIP TO BEAMS FIXING
DETAIL 'F' FLASHOVER STRIP TERMINATION
DETAIL 'G' BIMETALLIC CONNECTION TO COPPER TAPE BRIDGE SOFFIT MOUNTING
CONST UNIT H14 PROJECT No. 134307
LOCATION BHL 73 430 A X
NOTES
1. THIS DRAWING RELATES TO THE OLE CONDUCTIVE ASSEMBLY COMPONENTS OF THE BRIDGE ONLY. FOR STRUCTURAL FIXINGS SEE CIVILS DRAWINGS. 134307-APB-DRG-ECV-143635.
FIT FOR CONSTRUCTION A
EIS3
OLE BRIDGE CROSS SECTION
O/BR 4552
NTS 2 BHL 72.8- 73.7
134307-APB-DRG-EOH-121443 C02

Figure 346: (top to bottom) Typical bridge drawings; cross section, plan and bonding detail

18.4.6. Conductor Schedule

The *conductor schedule* lists all of the contact wire, catenary, earth wire, RC and ATF wire types (section 11.16) and lengths to be used on a particular section of electrified railway. It is derived from information contained on the layout plan (section 18.4.1).

18.4.7. Bonding Design

Bonding Design is the design of all earthing and bonding arrangements (section 10.10) necessary to facilitate the safe and reliable operation of the electrified railway, in accordance with the earthing and bonding strategy (section 17.7.1). This includes the design of the traction bonding, and also the various ancillary bonding arrangements needed at stations, level crossings and other electrical and mechanical installations.

The resulting *bonding plan* shows the detailed arrangements for the traction earthing and bonding. For the reasons given in section 10.10 they often show signalling bonding as well. These *composite bonding plans* are generally owned by the signalling discipline, with input from signalling, OLE, civil and M& E Engineers.

Composite bonding plans are safety critical and are strictly controlled by the infrastructure manager.

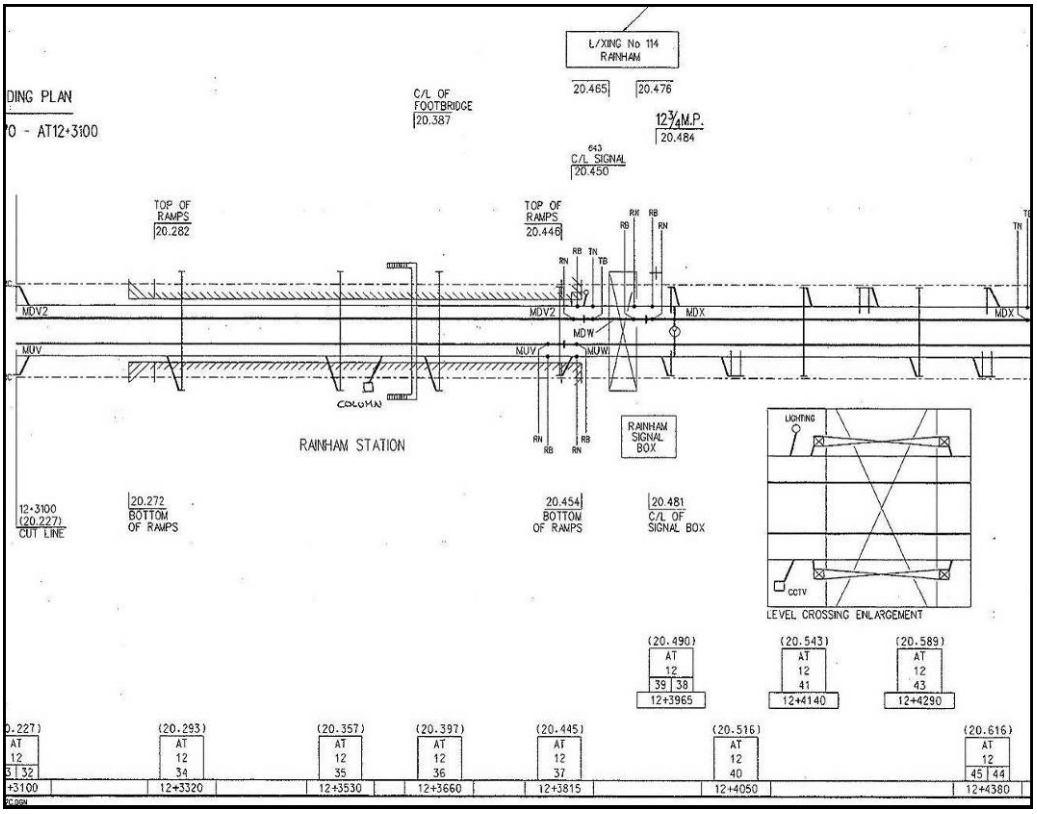


Figure 347: Typical composite bonding plan detail

18.4.8. Dropper Tables

The *dropper tables* detail the lengths and positions of droppers (section 11.16.4) in each span, to give the correct profile for the particular equipment type. They use the wire height information on the layout plan (section 18.4.1), and are derived either from standard dropper tables in the Basic Design (section 17.9.2), or calculated from first principles for non-standard spans. Dropper length calculations should include compensation for any point loads in span such as section insulators (section 11.6.1), and dropper positions must take account of any cut-in insulation (section 11.18).

18.4.9. Bills of Quantities

The *Bills of Quantities* (BoQ) are a breakdown of the assemblies shown on the cross sections (section 18.4.3) into components, for use in the procurement of materials. These can be presented by assembly, by component, by wire run or by construction unit; the format should be matched to the requirements of the procurement strategy (section 19.2.4).

18.4.10. Supporting Documents

An OLE design typically includes a number of other supporting documents. These include *hazard logs*, *design decision logs* and supporting narratives explaining the basis and rationale for the design.

18.4.11. Testing & Commissioning Strategy and Plan

Where changes are proposed to the feeding, switching and sectioning of OLE, or new electrification is to be constructed, a *Testing & Commissioning* (T&C) strategy is required for the work. This sets out the overall approach to testing and commissioning. This is followed by a more detailed plan, which specifies the steps to be taken to ensure that the system has been installed as per the design; particularly in terms of feeding, switching, sectioning and insulation strength.

The T&C plan will detail the tests to be carried out prior to re-energisation, and between energisation and the operation of trains on the new equipment (section 20). The plan should be created in conjunction with the OLE T&C engineer so that the logistical requirements are taken into consideration.

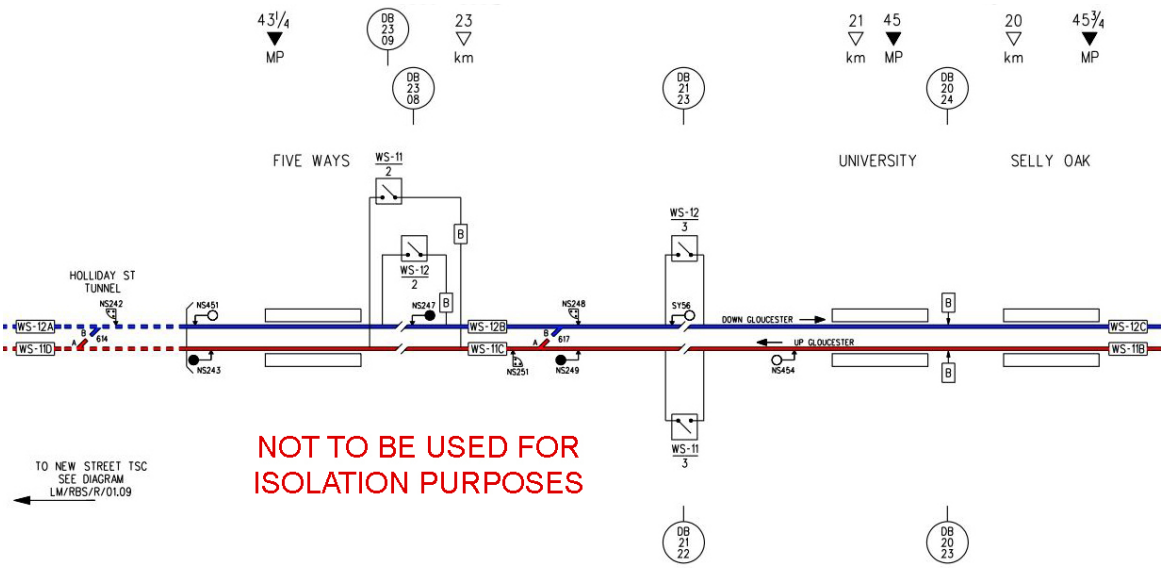
18.4.12. Operation & Maintenance Manuals

Where new equipment is introduced to the system as part of a construction activity, a set of *Operation and Maintenance* (O&M) manuals are required. These give details of the O&M requirements of the new equipment, so that operations and maintenance staff can conduct familiarisation training to maintain the equipment in line with standards and manufacturers recommendations.

In the UK, the O&M requirements for standard types of OLE are detailed in a set of standards documents. Therefore O&M manuals are only required if novel or proprietary items are introduced in the design.

18.4.13. Isolation Diagram and Isolation Instructions

At the completion of a project and prior to energisation, the section diagram (section 17.6.1) is converted to one or more *isolation diagrams*. These documents are used for taking isolations and are therefore safety critical; for this reason they are strictly controlled by the infrastructure manager.



Electrical Section or Sub-section	Lines Isolated	Limits of Isolation		Circuit Breaker / Switch		Remarks
		From	To	Open Remotely	Open Manually	
WS-11C	**Up Gloucester**	DB21/26	DB23/07	KS/WS-11 NS/WS-11	WS-11 3 WS-11 2	
WS-11D	**Up Gloucester**	DB23/11	BB00/87	KS/WS-11 NS/WS-11	WS-11 2	For this isolation, switch No. WS-5A WS-11D MUST NOT be in its alternate feed position.

NOT TO BE USED FOR ISOLATION PURPOSES

Figure 348: (top to bottom) Typical isolation diagram and associated switching instructions[217]

Alongside the isolation diagrams sit the *isolation instructions* - also known as *switching instructions*. These are a set of procedures detailing the steps to be taken to isolate and earth a particular section. These are also strictly controlled. Accompanying these are the *signalling isolation instructions*, which provide instructions to the signaller on the blocking signals and routes necessary to protect the isolation.

[217] Health warning added by author.

19. The Construction Phase

It is essential to fully consider the construction of OLE at the planning (section 17) and design (section 18) stages, since construction is by far the most costly part of the whole process. Given the difficulties in gaining approval for electrification schemes (section 7.4), efficient construction must be the constant goal, in terms of:

- Installation to design at the first attempt;
- Completion of as much work off-site as possible;
- As little unfinished work as possible;
- As little need for rework as possible;
- The minimum use of materials and plant;
- The fewest possible people involved.

More than any other factor, the productive use of time during track access periods will determine the efficiency and cost of an electrification scheme. Poor use of time on site will delay completion, increase cost and ultimately degrade the cost-benefit ratio to the point where further scheme approval can be jeopardised. Efficient working is only possible if the design is matched to the site and access constraints, and to the labour, materials and plant to be used.

The following sections focus on new electrification at 25kV AC on an existing mainline railway, but many of the activities described are also needed for the other types of project.

The overall construction sequence is as follows. Each installed asset should be formally assured against the design, before the location is cleared for the next step in the installation process:

1. Off-site works including fabrication;
2. Foundation installation;
3. Pile cap and transfer plate installation (if required);
4. Mast erection;
5. Boom erection;
6. *Dressing* of steelwork (adding support fittings);
7. Installation of support and registration (also known as *Small Part Steelwork* or SPS) assemblies;
8. Installation of switching and feeding connections;
9. Bonding installation;
10. Wiring installation;
11. Registration of wiring (which may be combined with wiring installation in a high output system - see section 19.12);
12. *Cutting in* of section insulators and other tensioned inline assemblies;
13. Final wiring adjustment;
14. Pantograph running check (*panning*).

Traction power and P&D works (section 19.16) are usually carried out ahead of, or in parallel with, the OLE works with connections made near the end of the process.

19.1. Early Contractor Involvement

Early Contractor Involvement (ECI) during the design phase can dramatically improve the efficiency of the construction phase, by ensuring that the design is fully aligned with the procurement and construction approach, and the plant to be used. For instance, there are several ways to support OLE on a four track railway, and the choice of portals (section 11.10.6) or TTCs (section 11.10.4) is dependent on construction access.

It is important to strike the right balance between the requirements of reliability and safety, as expressed in the electrical and mechanical designs, and construction efficiency. Without any input from the installer, the resulting design is likely to be misaligned with the construction process. Conversely, if the installation contractor is given complete freedom to define the design, there is a risk that short-term targets will be met at the expense of long-term reliability of the system. ECI can also improve procurement outcomes by giving greater visibility of global materials costs so that, for instance, the lowest cost steelwork can be prioritised in the design. ECI also tends to improve collaboration, allowing for risk-sharing and a common goal of reducing overall costs.

Equally, it is important that the designer is involved with the construction phase of the work. It is rare that an OLE design is installed without any changes being required; for instance as a result of unrecorded buried services, entailing the moving of a structure from its design position. It is essential that this design change is undertaken using a controlled process known as Construction Design so that critical design choices are not unknowingly reversed by a construction change.

19.2. Construction Planning

Particular construction factors that should be considered during design are:

- Foundation installation methodology;
- Plant availability and preferences;
- Details of site stores for materials and off-site assembly;
- Materials lead times and procurement logistics;
- Concrete availability and curing time;
- Site access for labour, plant and materials;
- Crane access and ground stability;
- Possession availability, including both routine possessions and longer blockades;
- OLE isolation & earthing requirements;
- Environmental receptors and constraints, including adjacent residents and wildlife;
- Integration with other activities, such as permanent way, civil, and signalling works.

Construction often takes place on an operational railway; in this case, closure and isolation opportunities may be infrequent and short in duration. The design must be staged to maximise these opportunities, with as much preparation work as possible carried out off-site, or on-site with trains running. Off-site activities can include cantilever fabrication, building pile caps (section 19.4.2) and pre-dressing of SPS (section 19.7). Droppers should also be pre-fabricated to the lengths specified in the dropper tables (section 18.4.8); on-site dropper fabrication should be avoided at all costs, since correct dropper length and spacing is critical to correct dynamic performance.

Any longer possessions or blockade opportunities must be planned and used with extreme care, as these will typically be booked several years in advance. The programme development (section 17.13) must ensure that sufficient designs and detailed access planning are in place to maximise the utilisation of these scarce opportunities.

The installer must also consider the loads imposed on OLE assemblies during construction - these can differ significantly from those in the final configuration (section 11.9), and the designer will not generally assess these temporary loads during the design phase. For example, temporary anchoring of an earth wire (section 10.10.1) prior to splicing and onward extension can impose significant and unusual loads on a mast.

19.2.1. Depot and Compound Locations

Choices about the number and location of OLE installation depots are based on a range of factors, including:

- The geographical scale of the work;
- The type of plant to be used - *Road Rail Vehicles* (RRVs) or foundation, steelwork and wiring trains (section 19.12);
- The type of plant to be used - Road Rail Vehicles (RRVs) or foundation, steelwork and wiring trains (section 19.12);
- The availability of land.

For projects using trains for installation, a traditional railhead depot is needed, ideally close to the centre of the route to be electrified to reduce travel time. The depot should be dedicated to, and fully under the control of, the electrification project. Facilities needed at this depot include:

- Sidings for stabling;
- Loading sidings with a concrete apron (with no overhead obstruction such as OLE);
- A maintenance shed with basic repair facilities such as lifting jacks;
- Train refuelling facilities;
- A large storage area for piles, masts, booms and SPS;
- A covered area with security for small materials, tools and high value items such as conductors (section 11.16);
- Racking for storage of small parts;
- A one-way system for delivery lorries, or a large turning circle;
- A large open area for fork-lift unloading of lorries;
- Office facilities for staff;
- Good local access roads for vehicles;
- A sheltered and heated fabrication area with IT for reviewing designs and drawings;
- Sufficient parking for staff.

Locations away from residential areas are preferred, since the depot is likely to be noisy at night. The depot should be staffed at all times, to allow any missing, damaged or lost items to quickly be replaced and so keep installation teams working. Consideration should be given to placing DEPs (section 10.12.1) close to RRAPs in electrified areas to speed up on-tracking of RRVs.

If space at the depot is at a premium, it is also possible to move the storage and/or fabrication function to a separate off-site facility, taking advantage of the good availability of industrial warehouse space for fabrication of OLE assemblies.

For projects using RRVs for installation, most of the depot facilities above are still required, but the sidings, maintenance shed and refuelling facilities are not needed. However the inability of RRVs to move long distances by rail (section 19.12.1) means that RRV compounds are required at frequent intervals along the route; each compound requires sufficient space to house plant, materials, welfare and parking, plus have an accessible road route without restrictions on lorry movements and access to the track via a *Road Rail Access Point* (RRAP). Each compound can typically cover around 5 route kilometres of railway.

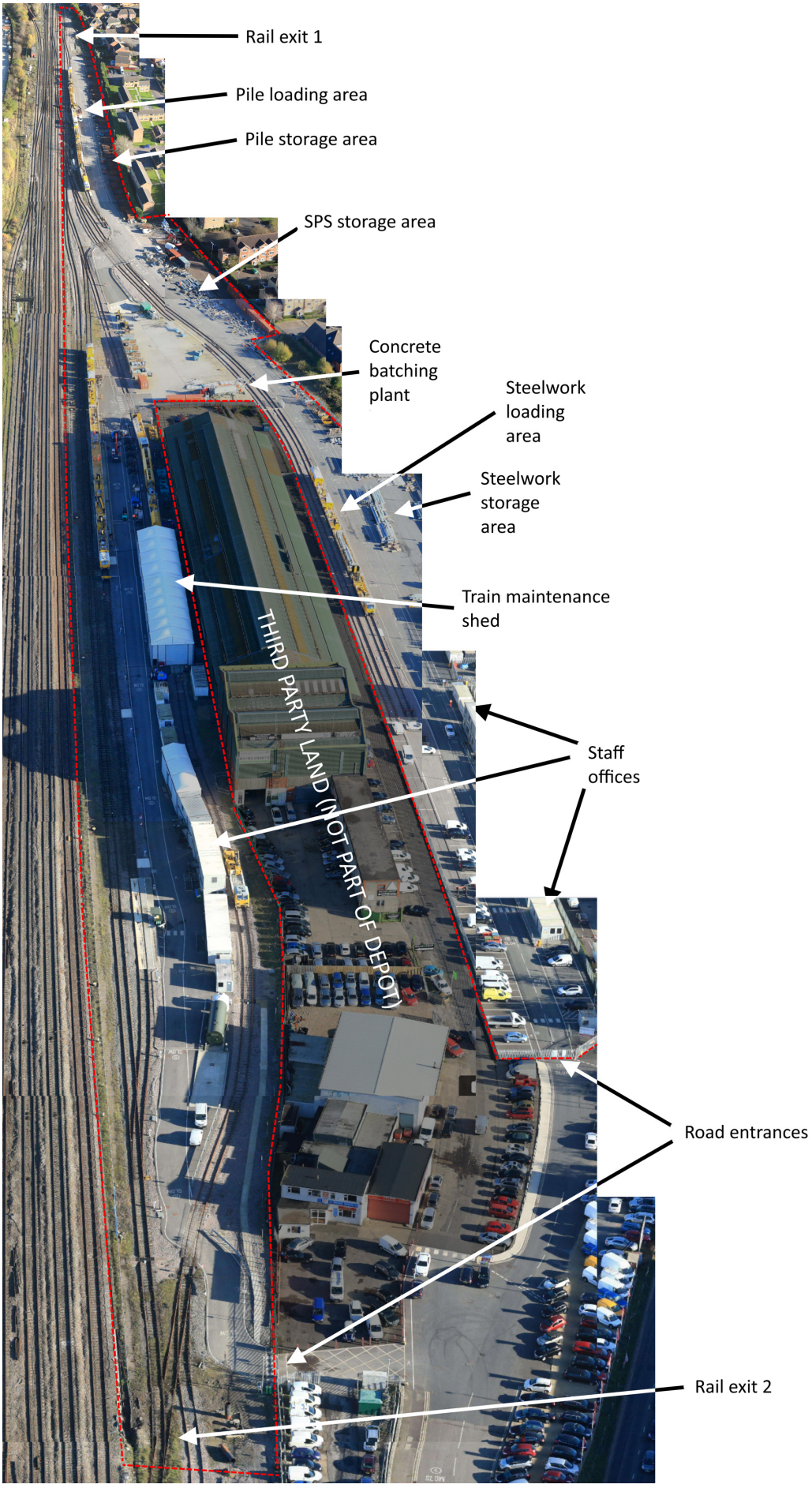


Figure 349: Aerial view of High Output Operating Base (HOOB) for OLE construction trains. Swindon, UK

19.2.2. Training Facilities

Construction and maintenance of OLE requires that sufficient competent people are available to carry out these activities. Each OLE system will have different setup requirements and specific training needs, and it is not practical to access operational equipment for training purposes.

Figure 350: OLE training spans - low level (foreground) and high level; Swindon, UK

For this reason most electrified railways will have a training facility, known in the UK as a *training span*. This typically consists of one or more spans of OLE erected in a convenient location away from the live railway. The OLE is permanently earthed (section 10.12.2) so that it is safe to work on at all times, and may consist of tension lengths installed at ground level, at full height, or ideally both. Track may be provided to permit RRVs to be on-tracked and simulate real-world construction and maintenance activities.

19.2.3. Construction Predecessors

A number of planning elements are required prior to beginning construction, including:

- Details of route access availability, including standard possession details and any required or available non-standard blockades;
- Safe system of work planning documents;
- Commercial agreements with strategic suppliers, including steelwork, conductors and cantilevers;
- Confirmation of materials delivery strategy - for instance elements may be delivered *just in time*, reducing store sizes but potentially increasing stockpile risk;
- Confirmation of logistics and materials handling availability (section 19.2.1);
- Permission for access to third party land, and attachment to third party structures;
- Any required legal consents to undertake the work (section 17.11);
- Communication plan for local residents (section 17.11.4);
- Earthing and bonding strategy (section 17.7.1 - for progressive bonding as construction progresses);
- Development of lean techniques to improve and refine the carrying out of individual tasks;
- Inspection and test plans.

The following design outputs must be available and fixed prior to beginning construction:

- Layout plans (section 18.4.1);
- Cross sections (section 18.4.3);
- Materials allocations (section 18.4.9);
- Foundation schedules (section 18.4.4);
- OLE bridge drawings (section 18.4.5);
- Dropper tables (section 18.4.8);
- Any additional documentation which is required by the infrastructure manager[218].

The rate at which design is produced must be matched to the rate at which construction is to proceed, and vice versa. If insufficient design is available, then the project will inevitably begin planning works and ordering materials at risk, and this leads to rework and increased costs.

19.2.4. Procurement and Materials Handling

Efficient procurement and materials handling processes are critical to the success of an electrification project; failure to take advantage of economies of scale when ordering, or to accurately match supply to demand, will increase costs significantly.

Ideally all materials should be ordered based on Approved For Construction designs (section 18), as this virtually eliminates wastage. However this approach increases overall programme durations (section 17.13) due to ordering lead times (section 19.2.4), and reduces economies of scale since items are not ordered in bulk.

An alternative approach is to pre-order items in bulk - but this must be done with care, so as to avoid excess wastage. Pre-ordering should only be carried out after an analysis exercise aimed at identifying likely quantities of each item, based on the design catalogue (section 17.9) and the characteristics of the route. The designer should be involved in this process, since they have the greatest understanding of how the design catalogue will be used on the project. This collaborative approach will influence the choice of materials storage, handling and stillage design. Even with such an approach, some wastage is inevitable; but this is less of an issue if the excess materials can be used on another route as part of a rolling programme of electrification (section 7.5). Pipe for OLE piles (section 11.11.4) can be bought in bulk and then called off to length and bossed once the design is finalised.

Regardless of which approach is adopted, long lead items should be identified and tracked throughout the project. Conductor lengths will be taken from the conductor schedule (section 18.4.6), and appropriate allowances should be made for wastage based on the wiring methodology (section 19.12) to be adopted. Conductor drums can be ordered to specific lengths to suit the particular wire run to reduce wastage.

All materials delivered to a depot or stores should undergo quality assurance checks on receipt, in case of poor fabrication, damage or incorrect ordering. This is a good time to label materials and divide them into storage bays. A robust warehouse labelling and racking system is essential to manage and maintain a stockpile sufficient to feed construction activities. Some projects use a tracking system based on QR codes securely attached to each component, thus providing full traceability of every item from its place of origin to its installed location. This approach requires rigid depot and site discipline, but is particularly useful if a batch of components later develops a mechanical or electrical defect requiring a recall, or if an installation quality issue emerges requiring all such components to be checked.

[218] NR/L2/ELP/27314 "Construction Assurance for Overhead Contact Systems"; Issue 2, September 2019; Network Rail

Figure 351: Storage racking in an OLE depot

The installation planning teams should be given the ability to interrogate the stocklist to check materials availability and delivery times for any given construction task, and to then reserve items, preventing two teams booking the same materials. A pre-fabrication team will then assemble components into the required assemblies, based on the AFC drawings and geometry information from previous site activities[219], and load the materials onto *stillages* in the correct order for unloading on site. These will either be loaded onto the train when needed (for train installation) or delivered to a secure compound at the nearest access point to the work (for RRV installation). The requisition system also needs the ability to revise the order when a design change occurs.

Components that are damaged or part of a defective batch must be suitably logged, labelled and quarantined in a separate area from the main materials storage, pending testing or return to the manufacturer.

19.3. General Construction Techniques

Construction techniques vary around the world, and depend on a number of factors. It is beyond the scope of this book to fully describe the construction process, but what follows is typical current UK construction practice. **The descriptions in this book are necessarily simplified, and should not under any circumstances be used to undertake actual construction**.

Particular care must be taken at each stage of the construction to ensure that partially-installed OLE is left in a safe state where it cannot interfere with the running railway. This is particularly important for items installed as height, such as cantilevers being restrained from swinging freely until conductors are installed, registration arms being secured to cantilevers prior to contact wire installation, and coils of feeder cable being secured prior to final connection. The relevant handback forms will be completed at the end of each installation shift - in the early construction stages this is to assure safe operation of non-electric traffic with partially completed OLE, whilst post-energisation, it performs the same assurance for all types of traffic.

[219] This can typically be done for SPS, cantilevers, switching base plates, false booms, stove pipes with cantilever brackets and similar assemblies.

19.4. Foundation Installation

The installation of foundations for OLE structures is one of the most challenging aspects of OLE construction. This is because - even with the most thorough planning and investigation - the nature of the ground in which the foundation sits (section 18.1.3) cannot be fully known prior to the time of installation. This means that the risks to construction timescales are high; just as with the rest of the construction sector, the challenges of *getting out the ground* should not be under-estimated. Foundation installation can account for 40% of total OLE system installation costs.

For portal structures (section 11.10.6) it is important to coordinate the installed positions of the foundations with the permissible across-track and along-track tolerances within the structure, to avoid a situation where the structure connections are over-stressed or installation cannot be completed.

A wide range of techniques are available around the world for foundation installation, and it is beyond the scope of this book to describe them all. The following sections describe typical current UK practice for installing various types of foundations.

The choice of RRVs or piling train for foundation installation is driven by many of the same access constraints that drive the choice of wiring plant, and this is discussed further in section 19.12.

19.4.1. Refusal Risk

One of the biggest challenges related to piled foundation is that of *refusal risk* - the likelihood that the pile will encounter solid rock or boulders during installation, preventing the installers from achieving the design depth (section 18.4.4) of the pile.

Unless steps are taken to mitigate this scenario, it can lead to abandonment of a pile, necessitating a costly and time-consuming redesign of the structure to an adjacent unobstructed location.

The risk of refusal must be assessed and mitigated as much as possible by assessment of GI data (section 18.1.3), but this is rarely sufficient on its own, since the data is never comprehensive. Careful planning of the works can further reduce the impact of the risk; for instance where a piling shift includes five piles in a low refusal-risk area and one with a known high risk of refusal, the high-risk pile can be pre-empted in the work planning. This could mean scheduling a pre-auger or - if the risk is low enough - installing the pile close to design depth. Techniques for further mitigating refusal risk are discussed in section 19.4.2.

Figure 352: Extreme example of pile refusal risk. Tilehurst, UK

Some piling techniques (section 19.4.2) result in a foundation deliberately being left partially out of ground between shifts. Any such plan must take into account the signal sighting requirements (16.7.1) of the route, since some piles could otherwise temporarily obstruct signal sighting. This is also the case for refusal risk near signals.

Whatever foundation type is being used, it is essential to mitigate the hazards of ground or track movement

during installation - particularly when it is occurring alongside an existing operational railway. Areas of poor stability which were identified in the design phase (section 18.1.3) may need to be monitored, both during installation and for a period after. Actual ground conditions encountered during installation should be used to inform monitoring decisions.

19.4.2. Piled Foundations

Driven steel tube piles (section 11.11.4) are the default choice for OLE foundations into good ground in the UK. Where there is more than one diameter available within the basic design range (section 17.9.2), the installer will often seek standardisation on a single size (typically 610mm diameter) to simplify storage, handling and plant requirements. While it is never possible for all of the foundations on a project to be of a single type, the designer and installer should make every effort to maximise the percentage of standard designs - some projects have achieved 95% use of driven steel tube piles, so keeping installation costs low.

Piles are typically stored and transported in a steel stillage, providing a safe and standardised means of containment. A piling schedule will be created using the foundation design schedule (section 18.4.4), with each pile allocated a specific place in the stillage matching its installed location on site. Checks will be made at every stage of the preparation, transportation and installation of the pile, to ensure that the right pile comes off the stillage and into the right location on site.

Figure 353: (l-r) stillage for TTC masts and booms, wiring train stillage for 610 diameter steel tubular piles

Steel tube piles are driven into the ground using an *Excavator-Mounted Vibrator* (EMV)[220] which can be mounted on an excavator RRV or piling train, and uses a combination of vibration and downforce to push the tube into the ground. This has the advantage of being much quieter than traditional drop-hammer piling techniques; this is an important consideration when working at night in populated areas, and is very efficient in granular soils. In cohesive soils and rock the EMV may not have sufficient capability to drive the pile to its design depth, in which case the EMV is replaced with a drop-hammer[221] to drive the pile the rest of the way.

As piling progresses the *blow count* data will show the amount of embedment per blow, giving a good indication of actual ground conditions. This should be compared with the previous geotechnical data (section 18.1.3), to refine the project's understanding of where different geologies lie, where rock is likely to be encountered, and to plan for potential refusals.

[220] This device is often referred to in the UK as a Movax head, after one of the companies that manufacture them.

[221] Often referred to as a Fambo head, after one of the companies that manufacture them.

Figure 354: (l-r) EMV on road-rail excavator, drop hammer on piling train consist

In areas of hard ground, driving the tube can be difficult. One option in these areas is to *pre-auger* using an auger bit diameter smaller than that of the tube[222]. The *arisings* from this operation are left in the hole to prevent collapse, and then the pile is driven in the normal way. OLE structures with higher vertical loads rely more on internal skin friction (section 11.11.4) and *soil plugging* effects to withstand loads, and this option should always be agreed with the designer prior to use. A *rock-drill auger* with *bullet teeth* provides an effective means of breaking through rock layers, and the flight angle and teeth setup can be varied to suit the geology[223].

Figure 355: (l-r) RRV with telescopic auger drill for 1m auger, pre-augering under way

Another option is the Elemex system, where a cutting shoe is welded to the end of a steel tubular pile prior to installation. The cutting shoe engages with the drilling head and cuts into the rock using air flush and rotary percussive techniques, while simultaneously removing the arisings using the flush. This approach creates an annulus around the pile, and although the resulting side- and end-bearing load capacities are likely to be high, resistance to torsion will be low. For this reason the technique should be used with care, especially for TTCs (section 11.10.4) and other torsionally-loaded structures.

Alternatively, a *rotary percussive drilling head* mounted on an RRV can be used to drive through rock layers, followed by immediate filling of the hole with concrete and driving the tube pile while the concrete is still wet. This technique is simpler than Elemex as there is no pre-welding or reassessment of loading required, since

[222] Typically 450mm.

[223] "Great Western Railway Electrification, UK: Foundations for Overhead Line Equipment", Esser, Lethbridge; 2020; Proceedings of the Institution of Civil Engineers - Civil Engineering.

the concrete is replacing the soil that would otherwise be in contact with the pile. A 750mm diameter drilling head is typically used to ensure that there is room in the annulus between the soil and the pile for the concrete to flow into when the pile is sunk.

Where a driven pile is close to its design depth but has suffered a refusal, the non-effective depth can be reduced by hand-excavating around the pile to 1m depth to remove any previously disturbed soil, and casting a concrete collar around the tube.

In some cases, the pile can reach solid rock a little short of design depth; in this case an assessment can be made that the pile has achieved the required capacity, if the rock has a higher capacity than the surrounding ground. The pile head can then be cut off, drilled on site and a steel pile cap installed. A purpose-made jig for cutting and a separate one for drilling is lifted into place using a crane RRV, simplifying the process and allowing several piles to be cut and drilled in a single shift. This technique is not a substitute for accurate assessment of ground conditions, and should be used only where necessary.

Figure 356: Cut-down steel tubular pile with drilling and pile cap. Moreton, UK

Concrete augered pile foundations (section 11.11.4) are usually used where the overturning moment exceeds the capacity of a steel tubular pile, where more end bearing capacity is required due to high vertical loads (for instance with large portals), or in areas where vibration is a concern. A steel casing (typically 1.8m long) is advanced into the ground prior to augering. This supports the soil around the top of the pile and prevents collapse, while providing a support for the rebar prior to the concrete pour.

A concrete auger causes less vibration than an impact hammer, but not necessarily less than an EMV. With good ground condition assessments as well as building and buried services sensitivity checks, conventional piling techniques can still be used if vibration monitoring is put in place.

19.4.3. Concrete Foundations

Concrete foundations have fallen out of favour in the UK in recent years. due to the logistics of bringing wet concrete to remote locations, the slow pouring and curing process, and the safety risks associated with open excavations. However concrete foundations are still widely used outside the UK, and are occasionally used in the UK where specific constraints prevent the use of piling techniques.

Installation of planted concrete masts (section 11.11.1) is undertaken by excavating a hole to the design depth with an RRV excavator, and then inserting the mast into the hole with an RRV crane. The mast is propped in the hole with wedges or a temporary grillage, and then concrete is poured into the hole. The risk of hole collapse must be mitigated, and this technique is only appropriate in the right ground conditions. The top of the hole

is *shuttered* with wooden planks to provide a rectangular former for the top of the foundation.

Installation of bolted base masts (section 11.11.2) follows a similar process, but rather than placing the mast into the hole, a cage of rebar is inserted in the hole, followed by the holding down bolts, which are temporarily held in the correct position using a template. Concrete is then poured and, once cured, the template is removed. Some designs require a two-stage pour, with the holding down bolts being secured in the second pour.

19.5. Structure Fixings

19.5.1. Overbridge Fixings

Fixings to overbridges (section 16.3.1) are typically installed using MEWPs or, if access is more generous, mobile scaffold towers. Pull-out tests should be undertaken to prove the strength of any resin anchor fixings.

19.5.2. Viaduct Fixings

Structures which are fixed to underbridges and viaducts (section 11.11.7) pose specific challenges related to the construction of the structure, its condition, and any heritage or aesthetic requirements.

Viaducts which require fixings on the outside of the structure create particular challenges for site access, due to the need for working at height and often over water. Depending on the height and location of the viaduct, access options include:

- Access from ground level using a tracked MEWP;
- Access from ground level using a scaffold tower;
- Access from track level using specialist rope operatives;
- Access from track level using bridge inspection cherry picker.

Figure 357: (clockwise from top left) Viaduct fixing access with tracked MEWP, scaffold tower, rope access, bridge inspection cherry picker

Figure 358: Core through brickwork of a viaduct. Radwell, UK

Depending on the information available on the structure, it may be necessary to undertaking *coring* prior to installation to confirm the depth and condition of brickwork.

For portal structures, it is particularly important to position fixing brackets accurately; viaduct construction often includes skewed elements, and for brick viaducts the brickwork is often uneven. For this reason bracket designs must be bespoke to the location, incorporating packing pieces and/or and adjustment mechanisms as necessary to assist construction. Drilling templates are often used to assist in drilling accurate holes, which are then blown clean in preparation for resin anchor fixings (section 16.3.1). Concrete viaducts will also have reinforcing bar which, as with overbridges, must be avoided during drilling.

The type of resin used is dependent on the situation; viaduct fixings typically use long large diameter holes, which require a slower setting product injected from the back of the hole outwards. Overbridge fixings require a faster setting resin so that fixings can be installed in the same shift. Dependent on the design it is often necessary to grout the bracket after installation to reduce the stress in the fixings. As with overbridges, pull-out tests should be undertaken on the resulting fixings.

Figure 359: Viaduct fixing template being prepared for drilling. Harpers Brook, UK

Figure 360: (l-r) Viaduct mast pedestals; side-bolted and through-bolted. Oakley Viaduct and Bromham Viaduct, UK

19.5.3. Tunnel Fixings

Tunnel fixings (section 16.5) also pose special challenges for installation. Factors which must be considered when planning the works include:

- Restricted access arrangements and volume of work to be undertaken;
- Working conditions in the tunnel and welfare arrangements;
- Restrictions on use of combustion engine plant;
- Ventilation requirements to replace air during works;
- Need for gas monitoring alarms.

Tunnel repair work may be required before fixing installation; this can involve removal, recasing, repointing, strapping, pinning or grouting of brickwork, to stabilise the tunnel ready for OLE support installation. As with viaducts, drilling templates and jigs are an essential aid to efficient installation of fixings in tunnels, and pull-out tests should be carried out on the installed bolts.

Figure 361: (l-r) Drilling drop bracket fixings in a tunnel with a bespoke drilling rig, fitting drop bracket

19.6. Steelwork Erection

The choice of RRVs or steelwork train for steelwork erection is driven by many of the same access constraints that drive the choice of wiring plant, and this is discussed further in section 19.12.

19.6.1. Masts

Mast installation is typically carried out using crane RRVs towing trailers which carry the masts, or a *Multi Purpose Vehicle* (MPV) consist including a crane vehicle and one or more mast carrying vehicles. Steel stillages allow multiple masts to be loaded onto the trailers.

Figure 362: (top to bottom) TTC booms on steelwork installation train, mast installation. Swindon and Didcot, UK

Masts can be lifted using slings or quick release hitches, and are placed on the lower holding down nuts (section 11.11.4). Any required rake (section 11.9) is applied, before the top holding down nuts are applied and tightened[224]. If slings are used, a MEWP may be required for access to release the slings.

Masts can be installed pre-dressed with ancillary wire brackets and cantilever brackets set to the correct position based in the finish foundation level (section 18.4.4) and the cross section (section 18.4.3). This can speed up construction, but may reduce the number of masts that can be carried to site; and care must also be taken to transport the masts in a way that does not damage the brackets. Structure number plates (section 12.1.1) should also be installed at this time.

19.6.2. Booms

Smaller booms, such as those for TTCs (section 11.10.4), are installed using the same RRV or MPV plant as for the mast installation. MEWPs will also be used during the installation process to enable installation staff to guide the boom into place and to install mast/boom connections. TTC booms can usually be loaded into the same steel stillages as the masts. Larger booms for portals are installed using a larger rail-mounted crane or road crane, depending on the availability of access at the site. Wherever possible booms should be pre-dressed with any bracketry that assists later stages of installation.

If a sufficiently large lay-down area is available at the site, it is possible to fabricate and lift an entire portal or TTC - masts, boom and SPS together - using a road crane. The largest booms require a *tandem lift* using two road-rail cranes, a procedure requiring significant additional planning and coordination on site.

Figure 363: Lifting a pre-assembled multi-track 305DC portal. Stafford, UK

[224] Portal and TTC masts are typically only partially torqued on installation, and full torque is applied only after the boom is installed (for portals) and the wiring installed (for TTCs).

19.7. Steelwork Dressing

This process installs all of the required support and registration equipment, and is an essential prerequisite for wiring. Efficient electrification demands that no wiring should take place until all SPS for that wire run is in place. It is important to place all equipment as close as possible to its design position, so that wiring can be installed to design height and stagger in one shift; this reduces the need for return visits for rework. Cantilevers will be pre-registered (allowing for any deviation once loaded with conductors) and secured using locking pins or cantilever clamps, so that they cannot move around under the action of wind, pending installation of wiring.

SPS installation is typically carried out with a combination of MEWPs (for installation staff access) and RRVs or MPVs (for lifting items into position). The RRV will tow trailers with stillages for cantilevers, stove pipes and tensioners, whereas the MPV will have stillages within its consist.

Figure 364: SPS installation. Didcot, UK

19.8. Vegetation Management

Vegetation growth poses a significant risk to OLE, with tree branches causing particular problems in terms of arcing and dewirement. It is essential that a vegetation management strategy is developed and implemented prior to erection of any wiring. This will typically involve cutting back of all vegetation to a fixed distance away from the railway. This process must be planned well in advance of construction, since it can involve cutting trees on third party land, as well as complying with legal prohibitions such as from TPOs (section 17.11.2) and restrictions during bird breeding season.

Once a vegetation management plan has been established, it must be maintained during the life of the system to prevent flashover problems building up over time.

19.9. Ancillary Wiring

Ancillary wiring (section 11.16.5) should ideally be installed before main wiring, as the lack of obstruction makes the process simpler, and provides early bonding continuity if an aerial earth wire is being used.

Unlike an auto-tensioned wire run, ancillary conductors are fixed termination (section 11.3), and so the installation process is slightly different to ensure that the tension in each span is equalised as far as possible.

The conductor is run out from a suitable anchor point at low tension using a wiring RRV and MEWPs, and is supported on temporary rollers at each structure. If the distance to be installed is more than a drum length (typically 500-1000m) then the new drum length is temporarily anchored at the mast adjacent to the splicing point, and spliced in (section 11.17.1) at the end of the installation.

The conductor is tied off at the second anchor location, and tension is applied with a pull-lift. The installer then works along the conductor, shaking the wire to remove any tension imbalance between spans or frictional drag. It is important to eliminate creep (section 11.16.1) in fixed termination wires, and to achieve this the tension is often set at 20% above the design value (taking into account ambient temperature) during this initial process, and then left for a period of 24 hours.

Once the wiring has settled, the installer returns and works back towards the pull-lift, again shaking each span to equalise tensions before moving the wire from the rollers to the conductor clamp while a MEWP applies the correct overall tension, adjusting for ambient temperature according to the design charts.

19.10. Bonding

Most line of route bonding is installed at ground level, using track trolleys to carry materials and the specialist drilling rig necessary for drilling rail connections (section 10.10). Bonding connections that are required to be installed on masts or booms - such as midpoint connections - are installed using MEWPs.

Bond connections must be made with particular care at locations with track circuits, since connection to the wrong rail can result in a wrong-side signal failure. Some bonding connections may be dependent on changes to the signalling system and/or bonding taking place first; in this case, one end of the bonding connection will be made, and the other left unconnected, but secured with an insulating boot until it is time for final installation.

Bonding cables should be routed so as not to create a tripping hazard, or leave the cable vulnerable to damage. Bonds should generally be routed under signalling cables so that maintenance access to these cable is not impeded.

Bonding connections at stations and other LV supply assets require coordination with the asset owner. The condition of existing electrical wiring can often require remediation as part of the works.

19.11. Switching and Feeding

Switching and feeding assemblies (section 11.7) are typically installed using long-reach MEWPs, supported by crane RRVs as necessary to lift larger switching bases into place. Isolator assemblies can be installed at any time after steelwork installation, but final connections can only be made after final registration (section 19.13) is complete. Hard standing and switching platforms will be installed using conventional civil engineering techniques.

Switching installation should be undertaken prior to wiring wherever possible, as the presence of wire runs makes access more complex.

Figure 365: (l-r) Correct lifting technique for a switching base, cross-track feeder installation with a long-reach MEWP. Corby, UK

Isolators are particularly sensitive to correct setup, to ensure that the isolator blade makes a good connection with the contacts, and that the actuation mechanism can move freely and without being overstressed; for this reason they should be assembled by the manufacturer in a factory environment wherever possible. Once assembled, transportation to site and installation requires particular care to avoid misalignment of the isolator blades. Correct operation of isolators should be checked on completion of the work. Motorised isolators should ideally be set up only once the LV power supply and SCADA (section 10.7.3) is connected, since adjusting the isolator in manual mode can result in misalignment once it is recommissioned in powered mode.

Cross-track feeds (section 11.7.2) can be partially assembled off-site, reducing work on site. Clearances between cross-track feeds and wire runs should be checked upon installation to ensure that minimum safety dimensions are met.

Particular care should be taken to ensure that switching and feeding connections are neither too slack, adding unnecessary weight to the wire run and running the risk that the conductor comes into contact with the pantograph; nor too tight, preventing free along-track movement of the wire run or unduly influencing height and stagger values.

Heights of all live parts should be checked to ensure that standing surface dimensions (section 10.9) are met.

19.12. Main Wiring

A number of options are available for installing the catenary and contact wire:

- RRV truck with *drum carrier* for each conductor, with friction or hydraulic brakes to install at low tension;
- Purpose-built RRV truck, installing at high or full design tension;
- MPV wiring train, installing at full design tension.

The choice of wiring method is project-specific; new electrification programmes may select a *high output* approach, using installation trains (section 19.12.3), whereas smaller projects are more likely to use RRV

techniques (section 19.12.1). Projects involving modification of existing OLE will take a more traditional approach using RRVs, since it is necessary to thread the new wire between existing wires, a process known as *flaking*. Projects may also choose a mixed approach, with wiring trains used in open route areas, and RRVs used in complex junction areas.

The order of wiring is another consideration, regardless of the plant used; some projects will install wires in descending order of height, which (dependent on the system design) can mean:

1. Crossover catenaries;
2. Running lines catenaries;
3. Crossover contact wires;
4. Running lines contact wires.

However this is not compatible with wiring a complete wire run at full tensions in a single shift, in which case running lines wire runs will be installed first, followed by crossover wire run installation using RRVs. Wiring trains are however capable of wiring simple crossovers if a tangential arrangement (section 11.5.6) and boom anchors (section 11.10.10) are used, so that no flaking is necessary.

The following sections assume installation of new sagged simple auto-tensioned equipment (sections 11.2 and 11.3) on an existing mainline railway; however the process is broadly the same for all equipment types. There are multiple variations on the methodologies outlined below, which are provided for illustration purposes only.

19.12.1. RRV Installation at Low Tension

This methodology uses OLE wiring RRV trucks which carry contact wire and catenary drums, and pay the wire out under a tension which is significantly below that of the system design. The tension applied by this approach is not a fixed value; instead the operator will operate a brake on the drum carrier to maintain sufficient tension to keep the wire from sagging excessively. The wires are maintained at the correct height as they leave the RRV via hydraulic guide arms, and the process is supported by MEWPs.

The typical process for this approach is:

1. Catenary and contact wire are terminated at one terminating anchor location - temporarily securing to the mast or boom;
2. First team runs the catenary out, supporting on temporary catenary rollers at each structure, and continues to the MPA;
3. Second team begins running out the contact wire, staying a few spans behind the catenary team and supporting the contact wire on temporary droppers;
4. When the catenary team reaches the MPA location, the catenary is initially dropped into a temporary roller. A third team then cuts the catenary into the MPA terminations;
5. Catenary and contact wire teams continue through the second half tension length, supporting the catenary on rollers at each structure, then supporting the contact wire on temporary droppers. Teams continue until the terminating anchor is reached;
6. Third team moves back to the initial anchor and installs the catenary in the tensioner unit, adjusting to final tension. Then the same process is carried out for the contact wire;
7. Third team moves towards the MPA, installing permanent droppers and clipping the contact wire into the registration arms;
8. At the second anchor location, the catenary is installed in the tensioner unit, and adjusted to approximate tension. Then the same process is carried out for the contact wire;
9. Third team moves from the MPA towards the second anchor, installing permanent droppers and clipping the contact wire into the registration arms;

10. Team returns on a subsequent shift to adjust the tensioners to final tension.

The advantage of this approach is that it maximises flexibility and minimises plant costs, since RRV trucks are readily available and can easily be on-tracked at any RRAP. The low tension means that the wires can be installed on the wooden drums delivered by the supplier, rather than needing to be respooled onto stronger metal drums.

However this approach has some disadvantages; the RRV is not able to provide full tension to the wires, due to the vehicle's lack of weight and adhesion. This means that a multiple-pass installation is needed, with initial tensioning and final tensioning carried in separate shifts, increasing overall time on site. RRV installation requires RRAPs to be available or created at regular intervals along the route (section 19.2.1). Each access point needs a secure compound big enough to store RRVs, fork-lifts and materials, as well as staff facilities and parking; and storage space for materials is likely to be more restricted that at a train depot. In the UK RRVs are only permitted to run within a possession, preventing early arrival on site. The lack of *Adjacent Line Open* (ALO) protection for staff means that adjacent lines must also be closed to traffic while work is taking place.

Tension distribution along the wire run is not achieved by the rollers alone, due to the weight distribution of differing span lengths; and it is not always possible to manually distribute the tension in the limited time available. Failure to equalise these tension differences leads to contact wire profile issues which will manifest as poor dynamic performance (section 11.1.2). On-site dropper length adjustment cannot then be avoided, but this can result in incorrect contact wire profiling or contact wire kinking which is difficult to remove. It can also be difficult to avoid twisting contact wires with smaller cross-sections, due to the low initial tension applied. Temporary droppers are often used in this scenario to reduce risk of contact wire twist.

Figure 366: Transferring contact wire from temporary rollers to registration arm. Bedford, UK

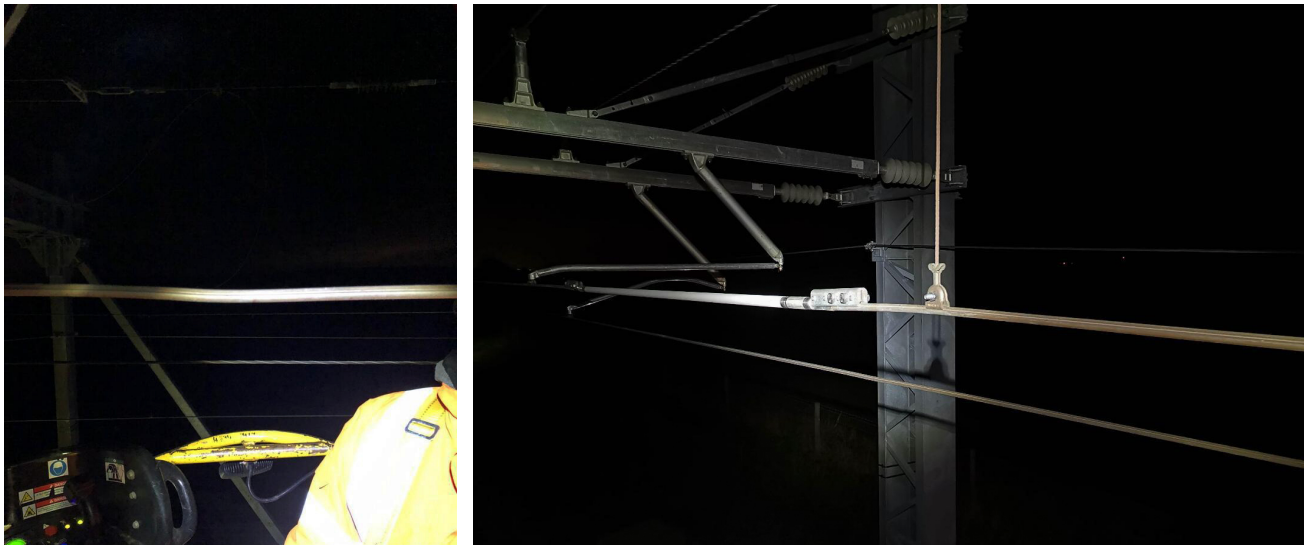


Figure 367: (l-r) Contact wire kinking in plain wire and at cut-in insulator

This wiring approach will typically take several shifts, and so is not favoured on operational railways with short access opportunities. It is however suited to branch lines where access may be more generous, or to green field railway construction.

19.12.2. RRV Installation at High or Full Tension

This methodology uses a specialist wiring RRV, supported by MEWPs and a scissor lift RRV. Unlike the traditional wiring RRVs, this plant is able to install at much higher tension because it is significantly heavier and so has greater adhesion. The tension achieved in the initial running of wire depends on the plant used; some RRVs operate at tensions somewhat below the full design tension - often referred to as ¾ tension, although in practice this is only approximate. Other RRV types such as the Zeck unit are capable of installing at full design tension.

The typical process for this approach is:

1. Terminate the catenary and contact wire at one terminating anchor location - temporarily securing to the mast or boom;
2. First team runs the catenary out, installing the catenary into support clamps at each structure. They continue to the MPA;
3. Second team begins running out the contact wire, staying a few spans behind the catenary team and supporting the contact wire on temporary droppers;
4. Third team begins installing the permanent droppers and clipping the contact wire into the registration arms, staying a few spans behind the contact wire team;
5. When the catenary team reach the MPA location, the catenary is initially dropped into a temporary roller. A follow-up MEWP then cuts the catenary into the MPA terminations;
6. Catenary, contact wire and dropper teams continue to proceed through the second half tension length, installing the catenary into support clamps at each structure, then supporting the contact wire on temporary droppers, then installing permanent droppers and registration arms. They continue until the terminating anchor is reached;
7. At the second anchor location, the catenary is installed in the tensioner unit, and adjusted to the final tension. Then the same process is carried out for the contact wire.

If a high tension wiring RRV is used rather than a full tension one, the final tensioning process will introduce changes in cantilever positions that will require further adjustment prior to completion.

Figure 368: High tension wiring with RRV and MEWPs. Bedford, UK

This approach brings obvious benefits over the low tension approach in terms of a reduced number of wiring steps and less time on site. A wire run can be fully installed in its final profile in a single shift, with only registration, cut-in activities and final measurements needed before testing and commissioning (section 20) can begin. Unlike with a wiring train (section 19.12.3), many of the flexibility advantages of RRV installation are also retained, as it still uses road-rail plant. This plant also allows for wiring using wooden drums, without the need for respooling; the unit feeds wire off the drums at low tension, and then pays the wire out while applying tension via a bull wheel mechanism. It is also easier to avoid wire twisting using this plant.

Figure 369: SRS/Zeck full tension wiring RRV

The main disadvantage of this approach is the limited availability of the plant, and the ongoing requirement for frequent RRAPs, support compounds and travel only within possessions.

19.12.3. Wiring Train Installation at Full Tension

This methodology uses a purpose-designed wiring train, typically comprising multiple MPVs including drum carriers, tensioning units, and scissor lift platforms for staff. The weight and adhesion of the vehicles makes installation at full tension possible. This train may be part of a *High Output Plant System* (HOPS)[225], or may be a standalone train.

The typical process for this approach is the same as for section 19.12.2, except that items 2 and 3 are merged, since the contact wire and catenary is run out and temporarily droppered by a single team, and the final droppering team (item 4) follow immediately behind.

[225] A HOPS typically comprises several separate *consists* - such as a foundation consist, a steelwork consist, a wiring consist and a final registration consist - each formed of one or more *Multi Purpose Vehicles* (MPVs).

Figure 370: (top to bottom) High output wiring train; registration consist, wiring consist - note ALO barriers in white. Goring, UK

The advantage of this approach is a reduction of time on site, as with section 19.12.2. Time on site is further reduced since a wiring train is also permitted to run in normal traffic, allowing it to be driven to site and then the possession taken around the train. A train can also carry all materials and staff on board, so that logistics are dealt with in a controlled stores and depot environment. This method encourages supply chain efficiency, since materials do not get delivered to lineside and then overlooked. Wiring trains with ALO safety barriers are also able to install OLE alongside operational lines, giving them greater flexibility than RRVs which require adjacent lines to be closed to traffic.

However the plant is much more expensive to buy than RRVs, and requires its own stabling, maintenance and loading facility; the high capital cost means that it typically pays for itself over more than one project, and is best used as part of a rolling programme (section 7.5). Flexibility is much lower since the train must travel from its depot to wherever it is required, and train paths must be booked well in advance of the work. The conductors must be respooled from the wooden drums they are supplied on, to stronger metal ones capable of withstanding the compressive forces created by wiring under full tension. This type of plant is also not suited to wiring complex track layouts with multiple turnouts.

This option is the most suitable for plain line areas where access is highly constrained, and productivity within a shift is the highest priority.

19.13. Registration

Once wiring is complete, it is necessary to revisit each structure to ensure that the final geometry is aligned with the design, since tensioning and droppering changes this geometry.

Registration is typically carried out on MEWPs, with geometry being checked from track level using a height and stagger gauge (section 18.1.1). Adjustments are made to the support and registration assemblies to ensure that the *acceptance criteria* for the location are met. Typical acceptance criteria include:

- Contact wire and catenary heights at the structures and at midspans (to confirm presag - section 11.2);
- Contact wire and catenary staggers (section 11.13.2);
- Contact wire gradients (section 11.13.1);
- Heel settings;
- Electrical clearances (section 10.8);
- Correct settings for along-track movement (section 11.3).

Registration should take place before cut-in activities, to ensure that assemblies such as section insulators are registered in their correct design position.

19.14. Cut-In Activities

Cut-in activities are those that are needed to install assemblies with tensioned connectors (section 11.17.1) into the wires. This should be carried out after wiring, since it is not practical or safe to do this when running the wires out. Assemblies with untensioned connectors will also be installed during this process. Installation is carried out using MEWPs or a wiring train scissor lift platform.
Assemblies installed include:

- Section insulators (section 11.6.1);
- Neutral sections (section 11.6.3);
- Cut-in insulators (section 11.18) - this activity also allows tensioners to be reset in the likely event that conductors have experienced creep (section 11.16.1) since installation;
- Equipotential and current-carrying jumpers (section 11.4).

Installation is achieved by clamping a *pull-lift* to the wire either side of the cut-in point, taking the tension on the pull-lift, and then cutting the wire and installing the assembly. Once the assembly is secured, the tension can then be released and the assembly geometry adjusted and finalised.

Figure 371: Pull-lift

19.15. Panning, Snagging and Works Completion

The panning stage involves a moving inspection of the completed installation from an elevated working platform on a vehicle that also has a pantograph fitted. This provides an initial basic check on OLE geometry and take-up of incoming and outgoing contact wires at overlaps (section 11.4) and crossovers (section 11.5).

Figure 372: Panning OLE to check registration. Oxley, UK

Other items checked during panning inspections include:

- Electrical clearances between live and earthed parts (section 10.8) such as overbridges and signal structures;
- Tightness of all bolt fittings;
- Heel settings (section 11.13.1);
- Dropper loadings;

- Pantograph travel through high-risk cut-in locations such as neutral sections (section 11.6.3) and section insulators (section 11.6.1);
- Correct hanging of jumpers (section 11.4) and feeders (section 11.7.2);
- Elimination of contact wire twists or kinks;
- Smooth transitions at any contact wire splices (for alterations to existing OLE).

It is inevitable that an installation team will encounter problems during the process of OLE installation; this could stem from a material supply issue, failure of a piece of plant, adverse weather conditions, third parties such as track renewals affecting track geometry, or a multitude of other factors. The end result of these issues is that OLE is rarely, if ever, installed 100% correctly at first pass. Problems can include missing items or incorrect geometry. These items must be identified as early as possible, but no later than panning inspection, and categorised as follows:

- Defects: items which affect the integrity, functionality or maintainability of the asset, or poses a risk to safety;
- Snags: all other construction quality issues.

As construction is completed, attention must be given to progressively identifying all defects and snags, rectifying defects first. This provides flexibility in terms of permitting commissioning activities to proceed while minor non-service-affecting snags are cleared later on.

19.16. Substations

Substations are generally easier to construct than OLE, since their off-track location means they can constructed without disruption to railway operation, there is far less working at height involved, and there are no tensioning processes. For these reasons substation construction is much closer to a conventional construction site, apart from the electrical works and the steps necessary to connect the substation to the OLE.

19.16.1. Civil Works

The initial stage of work creates the access road, fenced compound, earth mat and earth rods, then above that the concrete hard standing for transformers and buildings, any foundations necessary for switchgear masts, and cable trough routes for all of the cable runs. Trough routes between the substation and the lineside sealing end (section 10.2.9) locations are also installed at this stage. These will be built using conventional construction sector plant and processes, and the design must provide sufficient space for cranes and low loaders to move equipment around. Design of rural sites should pay special attention to local road access for heavy goods vehicles.

19.16.2. Mast Erection

Outdoor switchgear (section 10.2.7) is carried on a series of short masts. These will be installed either as part of the civil works, or shortly after they are complete, using a conventional lorry-mounted crane.

19.16.3. Containerised Building

The containerised building (section 10.2.1) will be constructed and fitted out with all switchgear, control and protection equipment at the supplier factory; this highly-controlled environment is designed to maximise the quality of the installation. The project team will visit the factory at key points in the fit-out to witness *Factory Acceptance Testing* (FAT). These tests are designed to demonstrate correct operation of circuit breakers, transformers and control equipment, and to progressively build validation assurance ready for entry into service.

19.16.4. Equipment Delivery

With the civil works complete, delivery of electrical equipment can take place. Depending on the type of substation, this can include:

- Transformers (section 10.2.3);
- Containerised building (section 10.2.1);
- Structure Mounted Outdoor Switchgear (section 10.2.7).

These will be delivered and installed using lorry-mounted cranes wherever possible, although larger buildings will need a full crane lift.

Figure 373: Containerised ATFS building being installed from low loader. Borehamwood, UK

19.16.5. Electrical Works

The substation now passes from being a civil construction site to an electrical fit-out site. All HV and LV cable connections, for both the live and neutral sides of the circuits, are laid in and connections made at each end. Outdoor switchgear is connected together using aerial busbars.

19.16.6. Grid Connections

Arrangements must be made for the connection of HV feeders at feeder stations (section 10.1.3), and LV power is required at all substations to provide power for SCADA (section 10.7), lighting and heating. These connections can be time-critical, with DNOs and NGCs having their own minimum timescales which must be factored into the programme (section 17.13).

19.16.7. Substation Bonding

The bonding of the substation site will now be carried out, connecting the substation equipment to the earth farm and to the adjacent railway through the neutral busbar.

19.16.8. OLE Connections

The final connection of the substation to the OLE (section 19.11) must be carefully coordinated with the OLE construction works to ensure that the lineside switching is complete and that the equipment is safe to connect to. Connections will be made using long-reach MEWPs or scaffold towers.

Once this work is complete, the site is handed over to the testing and commissioning team (section 20).

20. Testing, Commissioning and Entry Into Service

New OLE installations must undergo a number of electrical and mechanical tests prior to Entry Into Service (EIS). Depending on the extent of the changes and the level of novel design, any or all of the following tests may be needed. This process must be carefully planned, since it involves a complex sequence of tests conducted within restricted access to an operational railway. The tests themselves involve use of complex and sensitive specialists instrumentation, some of which must be installed on a test train. The complexity of planning and executing test trains on an operational railway should also not be underestimated, and the Testing & Commissioning (T&C) process is usually overseen by a separate specialist T&C team with experience of the activities within it.

20.1. Type Testing

Type Tests are carried out on components and assemblies of a new type, prior to their first use in a system, or use in a different system which will subject the item to new electrical or mechanical loads.

The nature of the type test will depend on the component, but will typically comprise one or more electrical and/or mechanical tests using loads significantly above the expected maximum loads in service. These tests may be to destruction, and are designed to establish the operational envelope of the component so that the maximum *working load* can be established and factors of safety confirmed.

The component may also be subjected to accelerated operating cycle tests, designed to simulate a working life in a much shorter space of time.

20.2. Snagging Walkout, Acceptance Tests and Completion Documents

It is an essential precursor for all of the subsequent tests that the construction is completed in accordance with the system and allocation designs (sections 17.9.1 and 18.4). This is usually confirmed by means of a walkout on site by senior representatives from design, construction, asset owner and maintainer. The walkout will identify any *snags* or corrections that need to be made prior to testing and entry into service. The walkout should be supported by completion documentation from the installer, recording the installed geometry, concrete *cube tests* and other important compliance evidence. These records will be checked against the acceptance criteria for the system, such as maximum stagger, gradient and other system parameters (section 19.13).

The later tests in this section should not be started until all elements of OLE construction are complete and all defects (section 19.15) have been cleared. Snags which do not affect the mechanical and electrical performance of the system can be cleared while testing continues.

20.3. Pressure Testing

Insulated cable elements of the OLE system, such as feeder cables at switching sites and ground level ATF routes, require electrical *pressure testing* to ensure that the insulation has not been compromised during installation. This test involves a voltage significantly above the operational level to be applied to the cores; for instance, UK standards[226] specify a test at either 75kV DC for 15 minutes, or 44kV AC for 5 minutes.

[226] NR-PS-ELP-00008 "Product Specification for High Voltage Cables and Accessories for Traction Supplies"; Issue 3, December 2005; Network Rail; appendix B.

20.4. Section Proving

Section proving is a series of tests to confirm that the electrical sectioning (section 10.3) is as designed. Each electrical subsection is switched in turn - starting from the feeder station and working outwards - and each OLE subsection is then proved dead and live. This is done using a *live line tester*, an insulated pole connected between the OLE and the traction return rail. The pole allows a small leakage current to flow, which shows live via an indicator LED. These tests also act to test the electrical integrity of the isolators (section 11.7) when open and closed; they take place during a complete railway shutdown with all non-essential staff removed from site; and due to the safety critical nature of the test it is essential that both the ECO (section 10.7) and the site testers follow a strict test plan, and that the live line tester is always connected to traction earth before any test - live or dead - takes place.

Figure 374: Section proving with a live line tester. Stockley, UK

20.5. Short Circuit Testing

Short circuit testing is designed to prove that the electrical protection (section 10.7.1) works as designed, and that all lineside equipment is fully immunised (section 10.4) under the most onerous conditions.

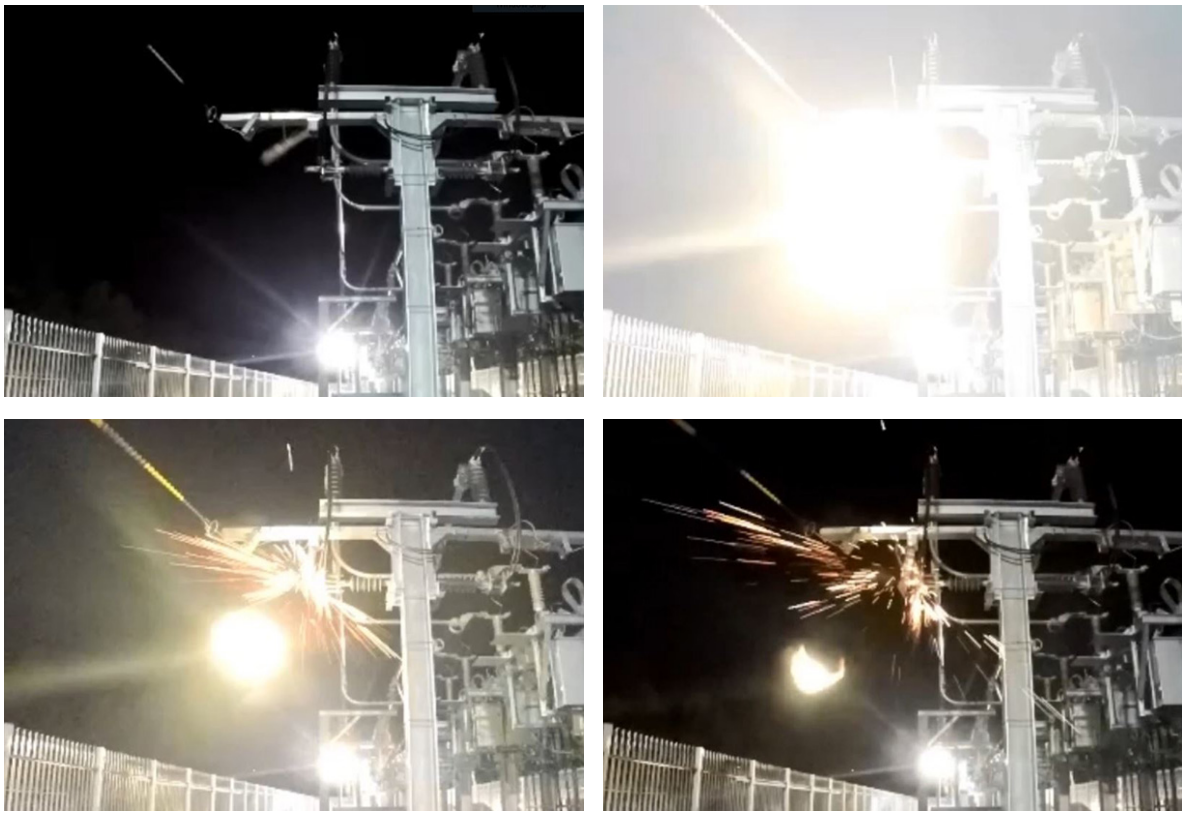


Figure 375: Short Circuit Testing - note plasma discharge in frames 3 and 4. Didcot, UK

One or more electrical faults are deliberately introduced to live OLE - usually using a portable isolator test rig

to connect the OLE to traction earth - and the performance of the electrical protection and the circuit breaker monitored during the subsequent electrical trip. Short circuit tests are carried out under the strictest of test conditions.

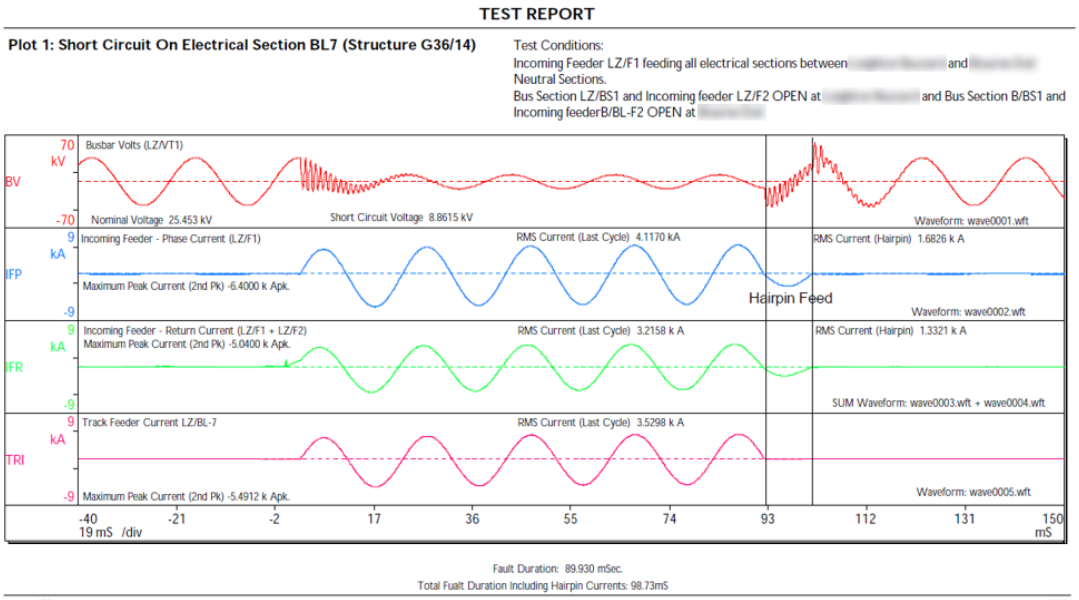

TEST REPORT
Plot 1: Short Circuit On Electrical Section BL7 (Structure G36/14)
Test Conditions:
Incoming Feeder LZ/F1 feeding all electrical sections between [redacted] and [redacted] Neutral Sections.
Bus Section LZ/BS1 and Incoming feeder LZ/F2 OPEN at [redacted] and Bus Section B/BS1 and Incoming feederB/BL-F2 OPEN at [redacted]
Busbar Volts (LZ/VT1)
BV
70 kV
-70
Nominal Voltage 25.453 kV
Short Circuit Voltage 8.8615 kV
Waveform: wave0001.wft
Incoming Feeder - Phase Current (LZ/F1)
IFP
9 kA
-9
Maximum Peak Current (2nd Pk) -6.4000 k Apk.
RMS Current (Last Cycle) 4.1170 kA
RMS Current (Hairpin) 1.6826 k A
Hairpin Feed
Waveform: wave0002.wft
Incoming Feeder - Return Current (LZ/F1 + LZ/F2)
IFR
Maximum Peak Current (2nd Pk) -5.0400 k Apk.
RMS Current (Last Cycle) 3.2158 k A
RMS Current (Hairpin) 1.3321 k A
SUM Waveform: wave0003.wft + wave0004.wft
Track Feeder Current LZ/BL-7
TRI
Maximum Peak Current (2nd Pk) -5.4912 k Apk.
RMS Current (Last Cycle) 3.5298 k A
Waveform: wave0005.wft
-40 -21 -2 17 36 55 74 93 112 131 150
19 mS /div
mS
Fault Duration: 89.930 mSec.
Total Fault Duration Including Hairpin Currents: 98.73mS

Figure 376: Voltage and current traces from short circuit test at a feeder station

Measurements taken during these tests include rise in earth potential, feeder current, fault clearance times and return current paths during the fault and data packet monitoring for the signalling system.

20.5.1. Tether Testing

Prior to any dynamic test, it is important to calibrate the aerodynamic behaviour of the pantograph. This is achieved by means of a *tether test*, where the pantograph is temporarily restrained by means of tether ropes attached between the pantograph carbon carrier (section 11.1) and the train roof. The ropes are set so that the pantograph will always be below contact wire height, and strain gauges are inserted into the ropes to measure the aerodynamic component of contact force. The train is then driven to full speed to measure this force. Once tether testing is complete the tethers are removed for the remainder of the dynamic testing.

Figure 377: (l-r) Pantograph tethers (red) being fitted, tethered pantograph ready for testing

20.6. Unpowered Mechanical Testing

This test is designed to validate the dynamic performance of the mechanical system[227], without introducing the additional risk of powering an electric train from the new OLE. A special test vehicle is used which carries an instrumented pantograph, and is pulled by a diesel locomotive. The test train will generally run at increasing speeds as the test proceeds, recording contact force and height and stagger data, as well as video of the pantograph. Any such train is treated as though it was electric for operational purposes, since it is in contact with the OLE.

20.7. Full Dynamic Testing

This test may also cover the areas described in the previous section, but will also confirm the expected electrical behaviour by using an electric train of the type planned for use on the electrified route. This is often combined with contemporaneous testing of lineside equipment to confirm immunisation levels (section 10.4) are as planned.

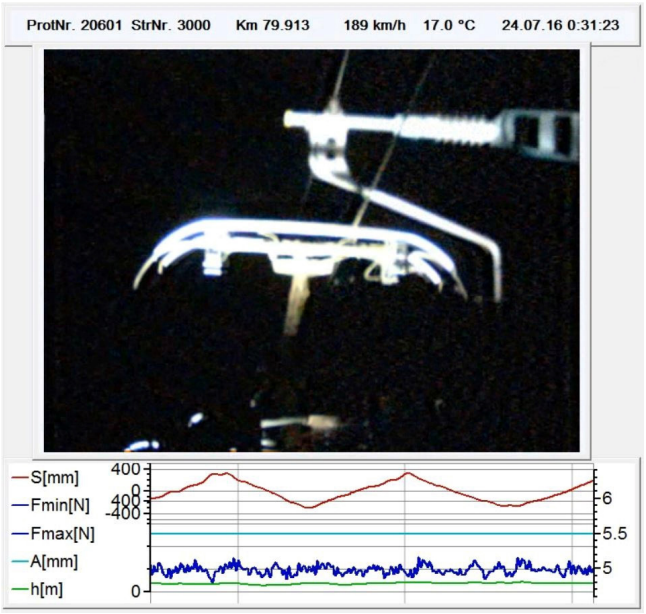


Figure 378: Typical output from instrumented pantograph on test train[228]

20.8. Entry Into Service

Entry Into Service (EIS) is the process of demonstrating that new electrification is safe to enter service and will perform as set out in the project requirements specification (section 17.2). The project will be required to produce evidence of the system readiness in accordance with applicable standards, safety and performance requirements. Evidence provided will include a range of risk assessments, safety justifications, construction completion evidence and test data.

In the UK and Europe the evidence is presented to one or more independent bodies, who will assess conformance with the relevant regulations and standards. In the EU a *Notified Body* (NoBo) is a country-appointed independent third party organisation which assesses the conformity of a railway system before it is entered into service. They do this by undertaking conformity assessments as set out in the applicable TSIs (section 11.1). In the UK an *Approved Body* (ApBo) carries out the same function against the applicable NTSNs. A *Designated Body* (DeBo) is a similar body, but which has competence to assess a railway system against the national rules (such as Railway Group Standards in the UK).

[227] In the EU these tests are carried out against BS EN50317:2012 "Railway Applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line"; 29 February 2012; BSI.

[228] Trace lines are stagger (red), height (green) and contact force (dark blue).

When the DeBo, NoBo and ApBo (as applicable to the project) are satisfied with the evidence presented by the project, they will make recommendations to the national regulator[229] for the system to be placed into service. The regulator has the final decisions as to whether this takes place.

The authorisation process should be seen as a gradual building of evidence towards EIS throughout the design, construction and testing processes. As with the rest of the process, early EIS planning is essential to a successful completion of the project.

20.9. As Built Documentation

An essential final step in the project is to update all of the AFC drawings with any changes made to the design during the construction process. These updates are included in the *As Built* (or *As Fitted*) drawings, which should accurately represent the final installed equipment. These drawings are transferred to the maintenance organisation to provide a baseline configuration for future works. Any future change to the system should then use the As Built drawings as the starting point, updating them in accordance with section 18 before producing a new set of As Built records.

[229] In the UK this is the Office of Rail and Road.

21. OLE Maintenance & Renewals

It is important to consider the maintainability of OLE at the planning and design stages, and OLE is relatively maintenance-free compared with other railway systems if designed correctly. It is usually inspected periodically, and any maintenance is carried out by small teams working from rail-mounted scissor lift or MEWPs (section 19).

Depending on the age and type of the equipment, regular maintenance items can include:

- Checking component condition, corrosion and position;
- Checking and cleaning insulators;
- Checking and adjusting height and stagger;
- Adjusting and cleaning neutral sections and section insulators;
- Checking mechanical and electrical clearances;
- Checking continuity of electrical connections;
- Checking wire tensions;
- Checking mechanical wear (for instance on hinge pins - typically checking a percentage of fittings);
- Security of nut and bolt fixings;
- Greasing connections[230];
- Structure painting (for older non-galvanised structures);
- Checking contact wire wear;
- Campaign change replacements of known problem components;
- Vegetation management (section 19.8).

Maintenance periodicity depends on age of equipment, traffic levels, criticality of the route, the matching (or otherwise) of pantographs and OLE, and the availability of access.

Contact wire will need replacing as part of a *midlife renewal* at around 25% to 33% wear, which is generally 20 to 30 years after installation. Leaving contact wire in situ significantly beyond this wear level creates a risk that dropper clips and other contact wire connections are impacted by the pantograph, and erodes the ability of the wire to withstand tension, leading to *parting* and dewirement. Midlife renewal will usually also address other issues which have come to light since installation.

More onerous rectification work is required after a dewirement. The team will be required to bring the OLE back into service as quickly as possible, and new wiring and support assemblies may be required. Each area has a store of materials for use in such incidents.

[230] Modern systems are usually grease-free.

22. Remote Condition Monitoring

The lack of redundancy in the OLE system makes it very important to understand and control the condition of both the infrastructure and the train-mounted equipment. In recent years an increased emphasis has been placed on the use of automated monitoring systems to augment the normal visual inspection processes.

22.1. Lineside Pantograph Monitoring

Monitoring of pantograph condition may be undertaken from a fixed lineside location using various techniques. *Panchex* is a system which has been used at critical locations on the UK electrified network since the 1980s, and is designed to detect faulty pantographs. The system comprises a linear sensor attached to the contact wire, which measures uplift (section 11.13.1) as each train passes. The system is synchronised with the *train describer* system which the signaller uses to identify each train. In this way a train with a faulty pantograph can be quickly taken out of service before the fault causes a dewirement.

The Panchex system has the disadvantage of requiring equipment to be placed in the OLE system itself, and requires ongoing maintenance. It is now being replaced with the *PanMon* and *Pantobot* systems, which use 3D photogrammetry techniques to detect faults in passing pantographs, and thus do not need any connection to the OLE.

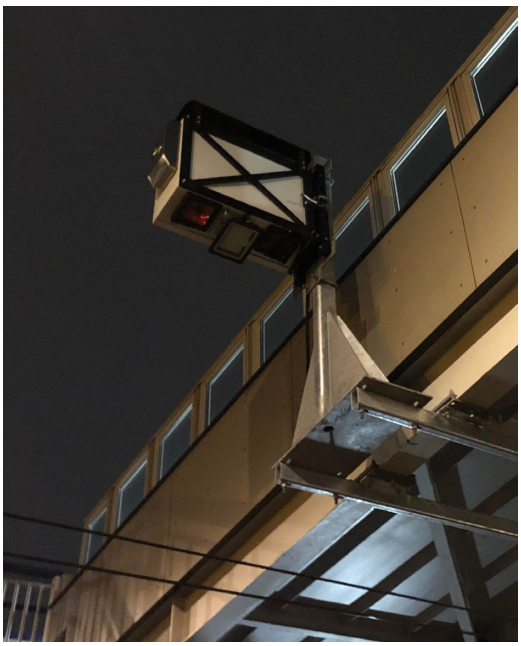


Figure 379: Ricardo Rail PanMon pantograph monitoring equipment. Glasgow, UK

22.2. Train-Mounted OLE Monitoring

Figure 380: High speed Shinkansen class 923 OLE monitoring train, a.k.a. "Dr Yellow"

Many administrations now use a dedicated OLE monitoring train, which passes over the electrified network at standard intervals and provides dynamic monitoring (section 20.6) through an instrumented pantograph. This is often tied into a Global Positioning System and allows faults to be accurately located for rectification. Some train operators are now applying these systems to a small number of service trains, which travel key routes at much higher frequencies and so can spot trends earlier than a dedicated train.

Appendix A

UK Electrification Build History

This list provides scheme extents and build dates for all known OLE installations in the UK.

Scheme extents are based on:

- Contemporary sources for recent schemes (2000 onwards);
- Various document sources for intermediate schemes (1985-2000);
- "The Age of the Electric Train" by J.C. Gillham (prior to 1985).

Completion dates are based on:

- Contemporary sources for recent schemes;
- "The Age of the Electric Train" by J.C. Gillham for historical schemes;
- "Electrifying the East Coast Route" by Peter Semmens for NER, GN and ECML schemes;

If no accurate date available from any source, 1st January on the year of opening is assumed. Opening date and status is based on first revenue-earning public electric service.

Categories are based on the following:

- *Tram* includes all UK schemes with a street-running element, or extensions of a scheme with a street-running element;
- *Metro* includes all self-contained non-tram systems, including DLR and Tyne & Wear;
- *Mainline* comprises all Network Rail-owned systems (including sections shared with LUL, Tyne & Wear Metro, Sheffield Supertram);
- *High speed* includes HS1, HS2 and the Channel Tunnel;
- *Heritage* includes all systems operating on heritage/tourist lines.

Status Codes are as follows:

- *Open* = currently in service;
- *Closed* = line closed;
- *Removed* = electrification removed;
- *Converted* = converted from one voltage and/or system to another;
- *WIP* = electrification under construction.

All items in red are to be confirmed.

Build	Voltage From	Voltage To	Route	Scheme	Stage	Category	Type	OLE Type	Date	Status
New Build	-	500V DC	Douglas - Groudle Glen	Manx Electric Railway		Heritage	Trolley		07/09/1893	Open
New Build	-	500V DC	Groudle Glen - Laxey	Manx Electric Railway		Heritage	Trolley		12/05/1894	Open
New Build	-	550V DC	Laxey - Snaefell	Snaefell Mountain Railway		Heritage	Trolley		21/08/1895	Open
New Build	-	500V DC	Laxey - Ballure	Manx Electric Railway		Heritage	Trolley		05/08/1898	Open
New Build	-	500V DC	Gynn - Fleetwood	Blackpool Tram		Tram	Trolley		14/07/1898	Open
New Build	-	500V DC	Ballure - Ramsay	Manx Electric Railway		Heritage	Trolley		24/07/1899	Open
New Build	-	6.7kV 25Hz AC	Morecambe - Heysham	L&YR		Mainline	OLE		13/04/1908	Removed
New Build	-	6.7kV 25Hz AC	Lancaster - Morecambe	L&YR		Mainline	OLE		01/07/1908	Removed
New Build	-	6.7kV 50Hz AC	London Victoria - Denmark Hill - London Bridge	LB&SCR electrification		Mainline	OLE		01/12/1909	Removed
New Build	-	500V DC	Grimsby (Corporation Bridge) - Immingham Town	Grimsby & Immingham Railway		Mainline	OLE		15/05/1912	Removed
New Build	-	500V DC	Immingham Town - Immingham Dock	Grimsby & Immingham Railway		Mainline	OLE		15/05/1912	Removed
New Build	-	500V DC	Immingham Town - Immingham Queens Bridge	Grimsby & Immingham Railway		Mainline	OLE		15/05/1912	Removed
New Build	-	6.7kV 50Hz AC	Battersea Park - Clapham Jct - Streatham Hill - Crystal Palace - Norwood Junction - Selhurst	LB&SCR electrification		Mainline	OLE		01/06/1912	Removed
New Build	-	6.7kV 50Hz AC	Tulse Hill - West Norwood	LB&SCR electrification		Mainline	OLE		01/06/1912	Removed
New Build	-	6.7kV 50Hz AC	Peckham Rye - Tulse Hill - Streatham Common	LB&SCR electrification		Mainline	OLE		01/06/1912	Removed
New Build	-	6.7kV 50Hz AC	Tulse Hill - Streatham Hill	LB&SCR electrification		Mainline	OLE		01/06/1912	Removed
New Build	-	3.5kV DC	Bury - Holcombe Brook	L&YR		Mainline	OLE		29/07/1913	Removed
New Build	-	1.5kV DC	Shildon Yard - Bowesfield	Newport - Shildon Railway		Mainline	OLE		01/07/1915	Removed
New Build	-	1.5kV DC	Bowesfield - Erimus Yard	Newport - Shildon Railway		Mainline	OLE		22/11/1915	Removed
New Build	-	1.5kV DC	Erimus - Newport	Newport - Shildon Railway		Mainline	OLE		01/01/1916	Removed
New Build	-	6.7kV 50Hz AC	Balham - Norbury - Selhurst - East Croydon - Coulsdon North	LB&SCR electrification		Mainline	OLE		01/04/1925	Removed
New Build	-	6.7kV 50Hz AC	Norwood Junction - West Croydon - Sutton	LB&SCR electrification		Mainline	OLE		01/04/1925	Removed
New Build	-	1.5kV DC	Manchester - Altrincham	MSJ&A Line		Mainline	OLE		11/05/1931	Removed
De-electrification	1.5kV DC	-	All NSR lines	Newport - Shildon Railway		Mainline	OLE		08/07/1935	Removed
New Build	-	1.5kV DC	London Liverpool Street - Shenfield	Great Eastern	Stage 1	Mainline	OLE	GE/MSW	26/09/1949	Open
New Build	-	1.5kV DC	London Fenchurch St - Bow Jct via Gas Factory Jct	London Tilbury Southend		Mainline	OLE	GE/MSW	26/09/1949	Open
New Build	-	1.5kV DC	Wath - Penistone	Woodhead Route		Mainline	OLE		04/02/1952	Closed
Conversion	6.7kV 25Hz AC	6.7kV 50Hz AC	Lancaster - Morecambe - Heysham			Mainline	OLE		17/08/1953	Removed
New Build	-	1.5kV DC	Manchester London Rd - Penistone, Reddish, Glossop	Woodhead Route		Mainline	OLE		14/06/1954	Closed
New Build	-	1.5kV DC	Penistone - Sheffield Victoria - Darnall	Woodhead Route		Mainline	OLE		20/09/1954	Closed
New Build		1.5kV DC	Darnall - Rotherwood	Woodhead Route		Mainline	OLE		03/01/1955	Closed
New Build	-	1.5kV DC	Shenfield - Chelmsford	Great Eastern	Stage 2	Mainline	OLE	SCS	11/06/1956	Open
New Build	-	1.5kV DC	Shenfield – Southend Victoria	Great Eastern		Mainline	OLE	SCS	31/12/1956	Open
New Build	-	25kV 50Hz AC	Wilmslow - Slade Lane	West Coast Mainline South	25kV test scheme	Mainline	OLE	Mark 1	26/10/1958	Open
New Build	-	25kV 50Hz AC	Colchester - Clacton & Walton	Great Eastern	25kV test scheme	Mainline	OLE	Mark 1	13/04/1959	Open
New Build	-	25kV 50Hz AC	Crewe – Manchester	West Coast Mainline South	Stage 1	Mainline	OLE	Mark 1	12/06/1960	Open
New Build	-	25kV 50Hz AC (parts) 6.25kV 50Hz AC (parts)	Helensburgh - Glasgow Queen Street - Airdrie; Dalreoch - Balloch; Westerton - Milngavie; Dalmuir Park - Hyndland via Westerton; Bellgrove - Springburn; Dalmuir Park - Yoker - Parkhead; High Street - Bridgeton	Glasgow suburban lines	Stage 1A	Mainline	OLE	Mark 1	05/11/1960	Open
Conversion	1.5kV DC	6.25kV 50Hz AC	London Liverpool St - Southend Victoria	Great Eastern		Mainline	OLE		06/11/1960	Open
New Build	-	25kV 50Hz AC (parts) 6.25kV 50Hz AC (parts)	Bethnal Green - Chingford; Hackney Downs - Enfield Town & Cheshunt			Mainline	OLE	Mark 1	21/11/1960	Open
New Build	-	25kV 50Hz AC	Cheshunt - Bishops Stortford & Hertford East			Mainline	OLE	Mark 1	21/11/1960	Open

Build	Voltage From	Voltage To	Route	Scheme	Stage	Category	Type	OLE Type	Date	Status
Conversion	1.5kV DC	25kV 50Hz AC	Shenfield - Chelmsford	Great Eastern		Mainline	OLE	-	20/03/1961	Open
De-electrification	500V DC	-	All G&IR Lines	Grimsby & Immingham Railway		Mainline	OLE		01/07/1961	Removed
Conversion	1.5kV DC	6.25kV 50Hz AC	London Fenchurch St - Bow Jct via Gas Factory Jct	London Tilbury Southend		Mainline	OLE	-	06/11/1961	Open
New Build	-	25kV 50Hz AC (parts) 6.25kV 50Hz AC (parts)	Gas Factory Jn - Shoeburyness; Barking - Pitsea via Grays; Barking - Forest Gate Jn	London Tilbury Southend		Mainline	OLE	Mark 1	06/11/1961	Open
New Build	-	25kV 50Hz AC	Crewe – Liverpool	West Coast Mainline South	Stage 2	Mainline	OLE	Mark 1	01/01/1962	Open
New Build	-	25kV 50Hz AC (parts) 6.25kV 50Hz AC (parts)	Glasgow Central - Motherwell via Uddingston; Cathcart Circle; Cathcart - Neilston High; Mount Florida - Newton	Glasgow suburban lines	Stage 1B	Mainline	OLE	Mark 1	27/05/1962	Open
New Build	-	25kV 50Hz AC	Upminster - Ockendon - Grays	LTS		Mainline	OLE	Mark 1	18/06/1962	Open
New Build	-	25kV 50Hz AC	Stafford - Crewe	West Coast Mainline South	Stage 3a	Mainline	OLE	Mark 1	07/01/1963	Open
New Build	-	25kV 50Hz AC	Chelmsford - Colchester	Great Eastern	Stage 3	Mainline	OLE	Mark 1	01/03/1963	Open
New Build	-	25kV 50Hz AC	Lichfield - Stafford	West Coast Mainline South	Stage 3b	Mainline	OLE	Mark 1	22/10/1963	Open
New Build	-	600V DC	Town End - Glory Mine	Crich Tramway Village		Heritage	Trolley		01/01/1964	Open
New Build	-	25kV 50Hz AC	Nuneaton - Lichfield	West Coast Mainline South	Stage 3c	Mainline	OLE	Mark 1	02/03/1964	Open
New Build	-	25kV 50Hz AC	Rugby - Nuneaton	West Coast Mainline South	Stage 3d	Mainline	OLE	Mark 1	16/11/1964	Open
New Build	-	1.5kV DC	Darnall - Tinsley Yard	Woodhead Route		Mainline	OLE		30/05/1965	Closed
New Build	-	25kV 50Hz AC	Cheadle Hulme - Macclesfield	West Coast Mainline South	Stage 4	Mainline	OLE	Mark 1	14/06/1965	Open
New Build	-	25kV 50Hz AC	London Euston - Rugby inc Northampton Loop	West Coast Mainline South	Stage 5	Mainline	OLE	Mark 1	06/12/1965	Open
De-electrification	6.7kV 50Hz AC	-	Lancaster - Morecambe - Heysham			Mainline	OLE		01/01/1966	Removed
New Build	-	25kV 50Hz AC	Wolverhampton - Stafford & Bescot; Portobello Jct - Bushbury Jct	West Coast Mainline South	Stage 6	Mainline	OLE	Mark 1	18/04/1966	Open
New Build	-	25kV 50Hz AC	Colwich - Macclesfield via Stone	West Coast Mainline South	Stage 7a	Mainline	OLE	Mark 1	05/12/1966	Open
New Build	-	25kV 50Hz AC	Stone - Norton Bridge	West Coast Mainline South	Stage 7b	Mainline	OLE	Mark 1	05/12/1966	Open
New Build	-	25kV 50Hz AC	Rugby - Wolverhampton via Birmingham	West Coast Mainline South	Stage 7c	Mainline	OLE	Mark 1	06/12/1966	Open
New Build	-	25kV 50Hz AC	Birmingham - Walsall	West Coast Mainline South	Stage 7d	Mainline	OLE	Mark 1	06/12/1966	Open
New Build	-	25kV 50Hz AC	Aston - Stechford	West Coast Mainline South	Stage 7e	Mainline	OLE	Mark 1	15/12/1966	Open
New Build	-	25kV 50Hz AC	Glasgow - Gourock & Wemyss Bay	Glasgow suburban lines	Stage 2	Mainline	OLE	Mark 2	05/06/1967	Open
New Build	-	25kV 50Hz AC	Clapton Jct - Cheshunt Jct	Lea Valley		Mainline	OLE	Mark 3	05/05/1969	Open
Conversion	1.5kV DC	25kV 50Hz AC	Manchester Oxford Rd - Altrincham	MSJ&A Line		Mainline	OLE		03/05/1971	Removed
New Build	-	25kV 50Hz AC	Wolverhampton North Jct - Oxley	West Coast Mainline South		Mainline	OLE		01/01/1972	Open
New Build	-	550V DC	Beamish Loop	Beamish Open Air Museum		Heritage	Trolley		01/01/1973	Open
New Build	-	120V DC	Seaton - Colyton	Seaton Tramway		Heritage	Trolley		01/01/1973	Open
New Build	-	25kV 50Hz AC	Bamfurlong Jct - Preston (Freight Only)	West Coast Mainline North	Stage 2	Mainline	OLE	Mark 3a	23/07/1973	Open
New Build	-	25kV 50Hz AC	Weaver Jct - Bamfurlong Jct (Freight Only)	West Coast Mainline North	Stage 1	Mainline	OLE	Mark 3a	23/07/1973	Open
New Build	-	25kV 50Hz AC	Weaver Jct - Preston (Passenger)	West Coast Mainline North	Stage 3	Mainline	OLE	Mark 3a	23/07/1973	Open
New Build	-	25kV 50Hz AC	Preston - Motherwell; Hamilton Circle; Uddingston - Wishaw via Bellshill; Motherwell - Whifflet	West Coast Mainline North	Stage 4	Mainline	OLE	Mark 3a	22/04/1974	Open
New Build	-	25kV 50Hz AC	Lanark Jct - Lanark			Mainline	OLE	Mark 3a	06/05/1974	Open
New Build	-	25kV 50Hz AC	Glasgow West St - Muirhouse Jct			Mainline	OLE	Mark 3a	01/01/1975	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Gidea Park - Shenfield	Great Eastern		Mainline	OLE	-	01/01/1976	Open
New Build	-	25kV 50Hz AC	Drayton Park - Welwyn Garden City & Hertford North	Great Northern Suburban	Stage 1	Mainline	OLE	Mark 3a	08/11/1976	Open
New Build	-	25kV 50Hz AC	Witham - Braintree			Mainline	OLE	Mark 3a	31/10/1977	Open
New Build	-	25kV 50Hz AC	Melton Jct - Edwalton	RIDC Melton (Old Dalby Test Track)		Private	OLE	Mix	01/01/1978	Open

Build	Voltage From	Voltage To	Route	Scheme	Stage	Category	Type	OLE Type	Date	Status
New Build	-	unknown	Dudley	Black Country Living Museum		Heritage	Trolley		01/01/1978	Open
New Build	-	25kV 50Hz AC	Welwyn Garden City - Royston	Great Northern Suburban	Stage 2b	Mainline	OLE	Mark 3a	06/02/1978	Open
New Build	-	25kV 50Hz AC	London Kings Cross - Finsbury Park	Great Northern Suburban	Stage 2a	Mainline	OLE	Mark 3a	06/02/1978	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Dalmuir Park - Yoker	Glasgow suburban lines		Mainline	OLE	-	01/01/1979	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Finnieston - Parkhead inc Bridgeton branch	Glasgow suburban lines		Mainline	OLE	-	01/01/1979	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Bellgrove - Springburn	Glasgow suburban lines		Mainline	OLE	-	01/01/1979	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Pollokshields East - Cathcart	Glasgow suburban lines		Mainline	OLE	-	01/01/1979	Open
New Build	-	25kV 50Hz AC	Hertford North - Stevenage	Great Northern Suburban	Stage 2c	Mainline	OLE	Mark 3a	01/01/1979	Open
New Build	-	25kV 50Hz AC	Finnieston Jct - Glasgow Central Low Level - Rutherglen			Mainline	OLE	Mark 3a	05/12/1979	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Dalmuir Park - Finnieston via Westerton; Yoker - Jordanhill; Westerton - Milngavie	Glasgow suburban lines		Mainline	OLE		01/01/1979	Open
New Build	-	650V DC?	Heaton Park	Heaton Park Tramway		Heritage	Trolley		01/01/1980	Open
New Build	-	25kV 50Hz AC	Castlefield Jct - Trafford Park FLT			Mainline	OLE	Mark 3a	12/05/1980	Open
New Build	-	1.5kV DC	Haymarket - St James, Bank Foot, Heworth & South Shields	Tyne & Wear Metro		Metro	OLE		11/08/1980	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	London Liverpool St - Gidea Park; Shenfield - Southend	Great Eastern		Mainline	OLE	-	12/10/1980	Open
New Build	-	?	Carlton Colville	East Anglia Transport Museum		Heritage	Trolley		01/01/1981	Open
New Build	-	25kV 50Hz AC	Edgeley - Hazel Grove			Mainline	OLE	Mark 3c	01/06/1981	Open
Closure	-	-	Hadfield - Penistone, Wath, Sheffield Victoria, Tinsley, Rotherwood	Woodhead Route		Mainline	OLE		17/07/1981	Closed
New Build	-	25kV 50Hz AC	Mossend - Coatbridge FLT			Mainline	OLE	Mark 3b	11/08/1981	Open
New Build	-	25kV 50Hz AC	London St Pancras & Moorgate – Bedford	Midland Mainline		Mainline	OLE	Mark 3b	28/03/1983	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Hackney - Chingford			Mainline	OLE	-	23/01/1984	Open
Conversion	1.5kV DC	25kV 50Hz AC	Manchester - Hadfield	Woodhead Route (truncated)		Mainline	OLE	GE/MSW	10/12/1984	Open
Conversion	6.25kV 50Hz AC	25kV 50Hz AC	Bury Street - Enfield Town			Mainline	OLE	-	01/01/1984	Open
New Build	-	25kV 50Hz AC	Navarino Road Jct - Reading Lane Jct			Mainline	OLE	Mark 3b	01/01/1985	Open
New Build	-	25kV 50Hz AC	Freight Terminal Jct - Camden Road East Jct			Mainline	OLE	Mark 3b	01/01/1985	Open
New Build	-	25kV 50Hz AC	Colchester - Ipswich	Great Eastern	Stage 4	Mainline	OLE	Mark 3b	13/05/1985	Open
New Build	-	25kV 50Hz AC	Ipswich - Stowmarket	Great Eastern	Stage 5	Mainline	OLE	Mark 3b	22/07/1985	Open
New Build	-	25kV 50Hz AC	Wickford - Southminster			Mainline	OLE	Mark 3b	12/05/1986	Open
New Build	-	25kV 50Hz AC	Manningtree - Harwich			Mainline	OLE	Mark 3b	12/05/1986	Open
New Build	-	25kV 50Hz AC	Romford - Upminster			Mainline	OLE	Mark 3b	12/05/1986	Open
New Build	-	25kV 50Hz AC	Paisley - Ayr	Ayrshire Coast		Mainline	OLE	Mark 3b	29/09/1986	Open
New Build	-	25kV 50Hz AC	Hitchin - Huntingdon	East Coast Mainline	Stage 1	Mainline	OLE	Mark 3b	03/11/1986	Open
New Build	-	25kV 50Hz AC	Kilwinning - Ardrossan South Beach; Dubbs Jct - Byrehill Jct	Ayrshire Coast		Mainline	OLE	Mark 3b	24/11/1986	Open
New Build	-	25kV 50Hz AC	Stratford FLT			Mainline	OLE		01/01/1987	Closed
New Build	-	25kV 50Hz AC	Temple Mills Yard			Mainline	OLE		01/01/1987	Closed
New Build	-	25kV 50Hz AC	Canonbury Jct - Finsbury Park			Mainline	OLE	Mark 3b	01/01/1987	Open
New Build	-	25kV 50Hz AC	Dalston Kingsland - Camden Road West Jct	North London Line		Mainline	OLE	Mark 3b	01/01/1987	Open
New Build	-	25kV 50Hz AC	Stratford - Dalston Kingsland	North London Line		Mainline	OLE	Mark 3b	01/01/1987	Open
New Build	-	25kV 50Hz AC	Bishop's Stortford - Cambridge			Mainline	OLE	Mark 3b	19/01/1987	Open
New Build	-	25kV 50Hz AC	Ardrossan South Beach - Largs & Ardrossan Harbour	Ayrshire Coast		Mainline	OLE	Mark 3b	19/01/1987	Open
New Build	-	25kV 50Hz AC	Huntingdon - Peterborough	East Coast Mainline	Stage 2	Mainline	OLE	Mark 3b	13/04/1987	Open
New Build	-	25kV 50Hz AC	Stowmarket - Norwich	Great Eastern	Stage 6	Mainline	OLE	Mark 3b	11/05/1987	Open
New Build	-	25kV 50Hz AC	Watford Junction - St Albans Abbey			Mainline	OLE	Mark 3b	01/01/1988	Open
New Build	-	?	Coatbridge	Summerlee Museum of Scottish Industrial Life		Heritage	Trolley		01/01/1988	Open
New Build	-	25kV 50Hz AC	Royston - Shepreth Branch Jct			Mainline	OLE	Mark 3b	02/05/1988	Open
New Build	-	25kV 50Hz AC	Peterborough - Leeds via Doncaster	East Coast Mainline	Stage 3	Mainline	OLE	Mark 3b	12/08/1988	Open

Build	Voltage From	Voltage To	Route	Scheme	Stage	Category	Type	OLE Type	Date	Status
New Build	-	25kV 50Hz AC	Airdrie - Drumgelloch			Mainline	OLE	Mark 3b	01/01/1989	Open
New Build	-	25kV 50Hz AC	Seven Sisters - Tottenham South			Mainline	OLE	Mark 3b	01/01/1989	Open
New Build	-	25kV 50Hz AC	Doncaster - York	East Coast Mainline	Stage 4	Mainline	OLE	Mark 3b	23/09/1989	Open
New Build	-	25kV 50Hz AC	York - Newcastle	East Coast Mainline	Stage 5	Mainline	OLE	Mark 3b	01/01/1990	Open
New Build	-	25kV 50Hz AC	Stratford - Copper Mill Junction			Mainline	OLE	Mark 3b	01/01/1990	Open
New Build	-	25kV 50Hz AC	Stansted Jct - Stansted Airport			Mainline	OLE	Mark 3b	01/01/1990	Open
New Build	-	25kV 50Hz AC	Litchurch Lane Works, Derby	Litchurch Lane Works Test Track		Private	OLE	Siemens	01/01/1990	Open
New Build	-	25kV 50Hz AC	Newcastle – Edinburgh	East Coast Mainline	Stage 6	Mainline	OLE	Mark 3b	01/01/1991	Open
New Build	-	25kV 50Hz AC	Carstairs – Edinburgh	East Coast Mainline	Stage 7	Mainline	OLE	Mark 3b	01/01/1991	Open
New Build	-	25kV 50Hz AC	Drem Jct - North Berwick			Mainline	OLE	Mark 3b	08/07/1991	Open
Conversion	1.2kV DC	750V DC	Manchester Piccadilly - Manchester Victoria - Bury	Manchester Metrolink	Phase 1	Tram	OLE		06/04/1992	Open
Conversion	25kV 50Hz AC	750V DC	Manchester - Altrincham	Manchester Metrolink	Phase 1 (previously MJS&A)	Tram	OLE		15/06/1992	Open
New Build	-	25kV 50Hz AC	Cambridge – King's Lynn			Mainline	OLE	Mark 3b	28/08/1992	Open
New Build	-	25kV 50Hz AC	Dollands Moor Freight Terminal	Channel Tunnel enabling works		Mainline	OLE	Mark 5	01/01/1993	Open
New Build	-	25kV 50Hz AC	North Pole Jct - West London Jct	Channel Tunnel enabling works	West London Line	Mainline	OLE	Mark 3b	01/01/1993	Open
New Build	-	25kV 50Hz AC	Manchester Airport North Spur			Mainline	OLE	Mark 3b	01/05/1993	Open
New Build	-	25kV 50Hz AC	Lichfield - Birmingham New St; Aston - Redditch	Cross City Line		Mainline	OLE	Mark 3b	06/06/1993	Open
New Build	-	750V DC	Sheffield - Meadowhall, Halfway, Herdings Park, Malin Bridge & Middlewood	Sheffield Supertram		Tram	OLE		01/01/1994	Open
New Build	-	25kV 50Hz AC	North Pole Depot	Channel Tunnel enabling works		Mainline	OLE	Mark 3b	01/01/1994	Open
New Build	-	25kV 50Hz AC	Cheriton - Frethun	Channel Tunnel		High Speed	OLE	Channel Tunnel	19/05/1994	Open
New Build	-	?	Woodside - Taylor Street	Wirral Tramway		Heritage	Trolley		01/01/1995	Open
New Build	-	25kV 50Hz AC	Leeds - Bradford, Skipton & Ilkley	Leeds North West		Mainline	OLE	Mark 3b	30/09/1995	Open
New Build	-	25kV 50Hz AC	Manchester Airport South Spur			Mainline	OLE	Mark 3c	01/01/1996	Open
Conversion	750V DC	25kV 50Hz AC	Camden Road West Jct - Acton Central	North London Line		Mainline	OLE	Mark 3b	01/01/1998	Open
New Build	-	25kV 50Hz AC	London Paddington - Stockley Airport Junction - Heathrow Tunnel Jct	Heathrow Express		Mainline	OLE	Mark 3b	19/01/1998	Open
New Build	-	25kV 50Hz AC	Heathrow Tunnel Jct - Heathrow Airport	Heathrow Express		Mainline	OLE	Mark 3b	23/07/1998	Open
New Build	-	750V DC	Birmingham Snow Hill - Wolverhampton	Midland Metro	Phase 1	Tram	OLE		30/05/1999	Open
New Build	-	25kV 50Hz AC	Kensal Green Jct - Willesden Jct			Mainline	OLE	Mark 3b	01/01/2000	Open
New Build	-	750V DC	Croydon - New Addington, Wimbledon, Beckenham Jct & Elmers End	Croydon Tramlink		Tram	OLE		30/05/2000	Open
New Build	-	750V DC	Cornbrook - Eccles	Manchester Metrolink	Phase 2	Tram	OLE		09/01/2001	Open
New Build	-	1.5kV DC	Pelaw Jct - Sunderland - South Hylton	Tyne & Wear Metro		Mainline	OLE	SICAT	01/01/2002	Open
New Build	-	25kV 50Hz AC	Crewe - Kidsgrove	West Coast Route Modernisation		Mainline	OLE	UK1	27/09/2003	Open
New Build	-	±25kV 50Hz AC	Fawkenham Jct - Cheriton	Channel Tunnel Rail Link	Section 1	High Speed	OLE	HS1	28/09/2003	Open
New Build	-	750V DC	Nottingham - Phoenix Park & Hucknall	Nottingham Express Transit	Phase 1	Tram	OLE		01/03/2004	Open
New Build	-	25kV 50Hz AC	Haughhead Junction - Larkhall	Larkhall Branch Extension		Mainline	OLE	SICAT SA	25/07/2005	Open
New Build	-	±25kV 50Hz AC	Fawkenham Jct - St Pancras International	Channel Tunnel Rail Link	Section 2	High Speed	OLE	HS1	14/11/2007	Open
Conversion	25kV 50Hz AC	25kV 50Hz AC	Euston - Liverpool, Manchester	West Coast Route Modernisation		Mainline	OLE	UK1	01/01/2008	Open
New Build	-	25kV 50Hz AC	Tamworth - Armitage/Handsacre	Trent Valley Four Tracking		Mainline	OLE	UK1	08/09/2008	Open
Conversion	25kV 50Hz AC	25kV 50Hz AC	Glasgow (Shields Jct) to Gourock	Shields to Gourock (S2G) Mark 2 to SICAT		Mainline	OLE	SICAT SA	2008	Open
New Build	-	750V DC	Harbour City - Media City	Manchester Metrolink	Mediacity spur	Tram	OLE		20/09/2010	Open
New Build	-	25kV 50Hz AC	Airdrie - Haymarket	Airdrie to Bathgate (A2B)		Mainline	OLE	Mark 3d	25/10/2010	Open
Conversion	550V DC	600V DC	Gynn - Fleetwood	Blackpool Tram		Tram	OLE		01/01/2011	Open

Build	Voltage From	Voltage To	Route	Scheme	Stage	Category	Type	OLE Type	Date	Status
New Build	-	25kV 50Hz AC	Corkerhill - Paisley Canal	Paisley Canal Electrification		Mainline	OLE	Mark 3b	01/12/2012	Open
New Build	-	750V DC	Manchester Victoria - Rochdale	Manchester Metrolink	Phase 3a	Tram	OLE		01/01/2013	Open
New Build	-	750V DC	Manchester Piccadilly - Droylesden	Manchester Metrolink	Phase 3a	Tram	OLE		01/01/2013	Open
New Build	-	750V DC	Trafford Bar - St Werburgh's Road	Manchester Metrolink	Phase 3a	Tram	OLE		01/01/2013	Open
New Build	-	25kV 50Hz AC	Manchester Victoria - Newton-le-Willows	North West Electrification Programme	Phase 1	Mainline	OLE	Series 2	01/12/2013	Open
New Build	-	25kV 50Hz AC	Springburn - Cumbernauld	EGIP		Mainline	OLE	Series 2	01/05/2014	Open
New Build	-	750V DC	Edinburgh Airport - York Place	Edinburgh Tram	Phase 1A	Tram	OLE		31/05/2014	Open
New Build	-	750V DC	St Werburgh's Road - Manchester Airport	Manchester Metrolink	Phase 3b	Tram	OLE		01/11/2014	Open
New Build	-	750V DC	Droylesden - Ashton-under-Lyne	Manchester Metrolink	Phase 3b	Tram	OLE		01/11/2014	Open
New Build	-	25kV 50Hz AC	Rutherglen - Coatbridge	EGIP		Mainline	OLE	Series 2	01/12/2014	Open
New Build	-	25kV 50Hz AC	Manchester Victoria	North West Electrification Programme	Phase 2c	Mainline	OLE	Series 2	01/01/2015	Open
New Build	-	25kV 50Hz AC	Newton-le-Willows - Edge Hill	North West Electrification Programme	Phase 2a	Mainline	OLE	Series 2	01/03/2015	Open
New Build	-	25kV 50Hz AC	Huyton - St Helens - Wigan	North West Electrification Programme	Phase 2b	Mainline	OLE	Series 2	17/05/2015	Open
New Build	-	750V DC	Nottingham - Clifton	Nottingham Express Transit	Phase 2	Tram	OLE		25/08/2015	Open
New Build	-	750V DC	Nottingham - Toton Lane	Nottingham Express Transit	Phase 2	Tram	OLE		25/08/2015	Open
New Build	-	750V DC	Birmingham Snow Hill - Birmingham New St	Midland Metro	Phase 2	Tram	OLE		30/05/2016	Open
New Build	-	750V DC	St Peters Square - Manchester Victoria	Manchester Metrolink	Second City Crossing	Tram	OLE		01/02/2017	Open
New Build	-	±25kV 50Hz AC	Stockley - Maidenhead	Crossrail		Mainline	OLE	Series 1	22/05/2017	Open
New Build	-	±25kV 50Hz AC	Scours Lane - Didcot	Great Western Electrification Programme	Route Section 3	Mainline	OLE	Series 1	28/12/2017	Open
New Build	-	±25kV 50Hz AC	Kennet Bridge - Reading - Scours Lane	Great Western Electrification Programme	Route Section 1a	Mainline	OLE	Series 1	28/12/2017	Open
New Build	-	±25kV 50Hz AC	Maidenhead - Kennet Bridge	Great Western Electrification Programme	Route Section 1	Mainline	OLE	Series 1	28/12/2017	Open
New Build	-	25kV 50Hz AC	Gospel Oak - Barking	GOBLIN		Mainline	OLE	Series 2	15/01/2018	Open
New Build	-	25kV 50Hz AC	Preston - Blackpool	North West Electrification Programme	Phase 3	Mainline	OLE	Series 2	21/05/2018	Open
New Build	-	25kV 50Hz AC	Newbridge Junction - Glasgow Queen St via Falkirk High	EGIP		Mainline	OLE	Series 2	24/07/2018	Open
New Build	-	25kV 50Hz AC	Barnt Green - Bromsgrove			Mainline	OLE	Series 2	29/07/2018	Open
New Build	-	750V DC	Meadowhall South - Rotherham Central	Sheffield Tram-Train		Tram	OLE	Series 2 DC	25/10/2018	Open
New Build	-	±25kV 50Hz AC	Didcot - Swindon	Great Western Electrification Programme	Route Section 5	Mainline	OLE	Series 1	29/10/2018	Open
New Build	-	25kV 50Hz AC	Stirling - Alloa - Dunblane	Stirling Alloa Dunblane (SDA)		Mainline	OLE	Series 2	30/12/2018	Open
New Build	-	±25kV 50Hz AC	Swindon - Bristol Parkway	Great Western Electrification Programme	Route Section 5/6	Mainline	OLE	Series 1	02/01/2019	Open
New Build	-	±25kV 50Hz AC	Reading - Newbury	Great Western Electrification Programme	Route Section 2	Mainline	OLE	Series 1	02/01/2019	Open
New Build	-	25kV 50Hz AC	Manchester Deal St Jct - Preston via Bolton	North West Electrification Programme	Phase 4	Mainline	OLE	Series 2	11/02/2019	Open
New Build	-	±25kV 50Hz AC	Wootton Bassett - Chippenham	Great Western Electrification Programme	Route Section 7C	Mainline	OLE	Series 1	21/04/2019	Open
New Build	-	25kV 50Hz AC	Mildcalder Junction - Holytown Junction via Shotts	H2M Holytown to Midcalder		Mainline	OLE	Series 2	25/04/2019	Open
New Build	-	25kV 50Hz AC	Walsall - Rugeley	W2R		Mainline	OLE	Series 2	01/05/2019	Open
New Build	-	±25kV 50Hz AC	Patchway - Newport (excl. Severn Tunnel)	Great Western Electrification Programme	Route Section 8	Mainline	OLE	Series 1	15/12/2019	Open
New Build	-	±25kV 50Hz AC	Bristol Parkway - Patchway	Great Western Electrification Programme	Route Section 8	Mainline	OLE	Series 1	15/12/2019	Open
New Build	-	±25kV 50Hz AC	Newport - Cardiff	Great Western Electrification Programme	Route Section 9	Mainline	OLE	Series 1	04/01/2020	Open
New Build		±25kV 50Hz AC	Severn Tunnel	Great Western Electrification Programme	Route Section 8	Mainline	OLE	Series 1 / F+F ROCS	31/05/2020	Open
New Build	-	25kV 50Hz AC	Bedford - Kettering - Corby	Midland Mainline Electrification	Key Output 1	Mainline	OLE	UKMS125	16/05/2021	Open
New Build	-	25kV 50Hz AC	Cardiff Queen St - Rhymney (excl. Caerphilly - Lisvane & Thornhill) Cardiff Queen St - Coryton Cardiff Queen St - Treherbert, Aberdare and Merthyr Tydfil	Core Valley Lines Electrification		Metro	OLE	UKMS100	2022	WIP
Conversion	500V DC	550V DC	Douglas - Ramsay	Manx Electric Railway		Heritage	Trolley		unknown	Open
Conversion	500V DC	550V DC	Gynn - Fleetwood	Blackpool Tram		Tram	Trolley		unknown	Open
Conversion	25kV 50Hz AC	±25kV 50Hz AC	Kensal Green - Stockley	Paddington to Reading (P2R)		Metro	OLE		2021	WIP

Build	Voltage From	Voltage To	Route	Scheme	Stage	Category	Type	OLE Type	Date	Status
Conversion	25kV 50Hz AC	±25kV 50Hz AC	Pudding Mill Lane - Shenfield	Crossrail		Mainline	OLE		TBC	WIP
New Build	-	±25kV 50Hz AC	Royal Oak - Liverpool St	Crossrail	Shenfield Section	Metro	OLE	Alstom Cariboni, F+F ROCS	TBC	WIP
New Build	-	±25kV 50Hz AC	Pudding Mill Lane - Plumstead	Crossrail	Plumstead Section	Metro	OLE	Alstom Cariboni	TBC	WIP
New Build	-	25kV 50Hz AC	Plumstead - Abbey Wood	Crossrail	Abbey Wood Section	Metro	OLE	Alstom Cariboni	TBC	WIP

Appendix B

UK Dual Voltage Areas

A number of UK locations have dual voltage electrification, and their stray current mitigation measures are summarised below[1].

AC Isolation Transformers

AC isolation transformers (section 10.11.1) are fitted at:

- 25kV AC OLE on ECML to 750V DC 3rd rail on Moorgate Branch at Drayton Park;
- 2x25kV AC OLE on High Speed 1 to 750V DC 3rd rail on mainline at Dollands Moor freight yard, Ashford, Ebbsfleet and Fawkham Junction;
- 25kV AC OLE on WCML to 750V DC 3rd rail on North London Line (NLL) at Primrose Hill;
- 25kV AC OLE on NLL to 750V DC 3rd rail NLL at Acton Central;
- 25kV AC OLE on West London Line (WLL) and North Pole Depot to 750V DC 3rd rail WLL at Scrubs Lane;
- 25kV AC OLE on NLL to 660V DC 4th rail on London Underground at Willesden Junction.

DC Contactors

DC Contactors (section 10.11.2) are fitted at:

- 25kV AC OLE on Thameslink to 750V DC 3rd rail on Thameslink at Ludgate Cellars;
- Three Bridges depot (between earthed rails in depot and 25kV test facility).

Non-linear Resistors

Non-linear resistors (section 10.11.2) are fitted at:

- 25kV AC OLE on NLL to 750V DC 3rd rail on East London Line at Dalston to Highbury & Islington.

DC Stray Current Collection Mat, AC Foundation Insulation

DC Stray Current Collection Mats and AC Foundation Insulation (section 10.10.2) are fitted at:

- Adjacent 25kV AC OLE and 750V DC OLE on Manchester Metrolink at Manchester Victoria;
- Adjacent 25kV AC OLE on GEML and 750V DC 3rd rail on DLR between Bow Junction and Stratford. Stray current collection mats are not present on 100% of the route.

[1] "Electrification Infrastructure – Reducing Whole Life Cost: DC Stray Currents", M. Sigrist; 2014; Network Rail.

No Specific Measures

No specific measures are believed to be taken at:

- Shared and adjacent 25kV AC OLE on WCML and 660V DC 3rd/4th rail on London Overground between Euston and Watford Junction;
- Adjacent 25kV AC OLE on London Tilbury & Southend (LT&S) and 660V DC 4th rail on London Underground between Bromley by Bow and Upminster;
- 25kV AC OLE on WCML to 750V DC 3rd rail on Merseyrail at Hunts Cross West Junction;
- Adjacent 25kV AC OLE on GWML to 660V DC 4th rail on London Underground between Paddington and Royal Oak and at Ealing Broadway;
- Adjacent 25kV AC OLE on GWML and 750V DC 3rd rail at Reading;
- Adjacent 25kV AC OLE on ECML and 750V DC 3rd rail on NLL at Canonbury West Junction;
- Adjacent 25kV AC OLE on LT&S and 750V DC 3rd rail on Docklands Light Railway (DLR) between Christian Street Junction and Limehouse;
- Adjacent 25kV AC OLE on mainline and 750V DC OLE on Midland Metro at Birmingham New Street/Stephenson Street;
- Adjacent 25kV AC OLE on ECML and 1500V DC OLE on Tyne & Wear Metro at Manors, Chillingham Road/Heaton and Benton;
- Adjacent 25kV AC OLE on GEML and 660V DC 4th rail on London Underground at Stratford. Systems are directly bonded together via red bonds.

To Be Confirmed

The following interfaces are to be confirmed:

- Adjacent 25kV AC OLE on Edinburgh & Glasgow (E&G) and 750V DC OLE on Edinburgh Tram between Haymarket and Edinburgh Park;
- Adjacent 25kV AC OLE and 750V DC OLE on Manchester Metrolink at Manchester Piccadilly, Deansgate, Manchester Airport;
- Adjacent 25kV AC OLE on Crossrail and 750V DC 3rd rail on mainline between Woolwich and Abbey Wood;
- Shared and adjacent 25kV AC OLE and 750V DC 4th rail at Melton Rail Innovation & Development Centre (RIDC) (also known as Old Dalby Test Track) between Old Dalby and Widmerpool;
- Shared and adjacent 25kV AC OLE and 750V DC 4th rail at Bombardier Derby Litchurch Lane Works;
- Adjacent 25kV AC OLE on GEML/Crossrail and 750V DC 3rd rail on DLR between Bow Junction and Stratford;
- Adjacent 25kV AC OLE on mainline and 750V DC 3rd rail on DLR between Stratford Carpenter's Road North Junction and Stratford International.

Appendix C

UK Pantograph Types

This appendix describes the pantographs which are operational in the UK today, together with those which have been used on UK 25kV infrastructure in the past. Operational speeds quoted are maxima permitted in the UK – the pantograph may be used at higher speeds in other countries.

The details below are collated from a variety of sources. Individual train operators will often modify pantographs based on in-service experience, so these should be considered broad categories only.

AEI Cross-arm Pantograph

Figure C.1: AEI Cross-arm pantograph

Voltage	25kV AC
Use:	Mainline
In UK Since:	1960
Max Speed:	177km/h
Arm:	Two crossed diamond
No. of Strips:	2
Strip Spacing:	Unknown
Linkage Type:	Provided by twin arms
Suspension:	Primary/secondary
Secondary Suspension Type:	Twin plungers
Secondary Travel:	None?
Aerofoils:	None
Strip Material:	Unknown
Auto-Drop Device?	Assume No
Over Height Drop?	Assume No
Horn Mount:	Integral with carbons
Horn Type:	Live
Head Profile[1]:	GB profile
NTSN Compliant:	No
Fitted To:	Originally fitted to class 86, 87. All now replaced.
Notes:	No longer in use. All remaining pans are unserviceable on preserved rolling stock.

[1] "GB profile" denotes profile as per BS EN50367:2020 figure B.6; "Europan" denotes profile as per BS EN50367 Fig. A.6; "HS1 profile" denotes profile as per BS EN50367 Fig. B.3.

Stone-Faiveley AM/BR Pantograph

Figure C.2: Stone-Faiveley AM/BR pantograph with Brecknell Willis Head

Voltage	25kV AC
Use:	Mainline
In UK Since:	1959
Max Speed:	140km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	As per BW HS-P Mark 1
Linkage Type:	External bar links
Suspension:	Primary/secondary
Secondary Suspension Type:	As per BW HS-P Mark 1
Secondary Travel:	As per BW HS-P Mark 1
Aerofoils:	None
Strip Material:	As per BW HS-P Mark 1
Auto-Drop Device?	Yes
Over Height Drop?	Yes
Horn Mount:	As per BW HS-P Mark 1
Horn Type:	As per BW HS-P Mark 1
Head Profile:	As per BW HS-P Mark 1
NTSN Compliant:	No
Fitted To:	Class 81, 82, 83, 84, 85, 86, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 317/8, 318

Notes:	The above data are based on the current configuration of the AM/BR pantograph, which has been retro-fitted with a Brecknell Willis HS-P Mark 1 head. This pantograph was originally fitted with a different head, which used a spring parallelogram as the secondary suspension[2].

[2] "British Railways Electrification Conference London 1960: Railway Electrification at Industrial Frequency"; 1960; British Transport Commission; p147.

Brecknell Willis HS-A Pantograph

Figure C.3: Brecknell Willis HS-A pantograph

Voltage	25kV AC
Use:	Mainline
In UK Since:	1980
Max Speed:	225km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	300mm?
Linkage Type:	Internal 4th bar attached to chain at knuckle, internal bar link to head
Suspension:	Primary/secondary
Secondary Suspension Type:	Torsion bar on trailing arm
Secondary Travel:	65mm
Aerofoils:	On head
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	Yes
Horn Mount:	Integral with carbons
Horn Type:	Live
Head Profile:	GB profile
NTSN Compliant:	No
Fitted To:	Class 87, 89, 90, 91, 92, 317/1, /5, /6, /7, 319, 320, 321, 322, 323, 325, 332, 333, 370, 390, 769, Eurotunnel class 9
Notes:	Also known as BW high speed

Brecknell Willis HS-P Mark 1 Pantograph

Figure C.4: Brecknell Willis HS-P Mark 1 pantograph

Voltage	25kV AC
Use:	Mainline
In UK Since:	1995
Max Speed:	160km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	300mm
Linkage Type:	Internal 4th bar attached to chain at knuckle, internal bar link to head
Suspension:	Primary/secondary
Secondary Suspension Type:	Twin plungers
Secondary Travel:	40mm
Aerofoils:	On knuckle
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	Yes
Horn Mount:	Integral with carbons
Horn Type:	Live
Head Profile:	GB profile
NTSN Compliant:	No
Fitted To:	Class 334, 350/2, 357, 360 (some), 365, 375/6, 377, 378, 379, 380
Notes:	Also known as BW High Speed Plunger, Desiro Mk1

Brecknell Willis HS-P Mark 2 Pantograph

Figure C.5: Brecknell Willis HS-P Mark 2 pantograph

Voltage	25kV AC
Use:	Mainline
In UK Since:	2005
Max Speed:	175km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	300mm
Linkage Type:	Internal 4th bar attached to chain at knuckle, internal bar link to head
Suspension:	Primary/secondary
Secondary Suspension Type:	Twin plungers
Secondary Travel:	40mm
Aerofoils:	On knuckle
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	Yes
Horn Mount:	Integral with head frame (carbons decoupled from horns)
Horn Type:	Live
Head Profile:	GB profile
NTSN Compliant:	Yes
Fitted To:	Class 88, 331, 345, 350/1, 360 (some), 385, 387 (some), 700, 710, 717, 720, 730, 745, 755
Notes:	Also known as BW High Speed Plunger, Desiro Mk2

Brecknell Willis HS-P Mark 2 "Donuts" Pantograph

Figure C.6: Brecknell Willis HS-P Mark 2 "Donuts" pantograph

Voltage	25kV AC
Use:	Mainline
In UK Since:	2005
Max Speed:	175km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	300mm
Linkage Type:	Internal 4th bar attached to chain at knuckle, internal bar link to head
Suspension:	Primary/secondary
Secondary Suspension Type:	Twin plungers
Secondary Travel:	40mm
Aerofoils:	On knuckle
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	Yes
Horn Mount:	Integral with head frame (carbons decoupled from horns)
Horn Type:	Live
Head Profile:	GB profile
NTSN Compliant:	Yes
Fitted To:	Class 387 (some)
Notes:	Donuts (toroids) are fitted to reduce electrical stress for arcing to the roof in low wire height areas

Brecknell Willis HS-X Pantograph

Figure C.7: Brecknell Willis HS-X pantograph

Voltage	25kV AC
Use:	Mainline
In UK Since:	2015
Max Speed:	225km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	450mm
Linkage Type:	Internal 4th bar attached to chain at knuckle, internal bar link to head
Suspension:	Primary/secondary
Secondary Suspension Type:	Twin transverse springs
Secondary Travel:	~60mm
Aerofoils:	On knuckle
Strip Material:	Metallised carbon
Auto-Drop Device?	Yes
Over Height Drop?	Yes
Horn Mount:	Integral with head frame (carbons decoupled from horns)
Horn Type:	Live
Head Profile:	GB profile
NTSN Compliant:	Yes
Fitted To:	Class 397, 800, 801, 802, 803, 805, 807, 810 variants
Notes:	

Faiveley GPU Pantograph

Figure C.8: Faiveley GPU[3] pantograph

Voltage	25kV AC, 1.5 kV DC
Use:	High Speed
In UK Since:	1993
Max Speed:	300km/h (AC), 270km/h (DC)
Arm:	Single
No. of Strips:	2
Strip Spacing:	Unknown
Linkage Type:	External bar links
Suspension:	Primary/secondary/tertiary
Secondary Suspension Type:	Single plunger (secondary), twin plungers (tertiary)
Secondary Travel:	150
Aerofoils:	On head
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	No – mechanical height limit device provided
Horn Mount:	To secondary-sprung head
Horn Type:	Insulated
Head Profile:	HS1 profile
NTSN Compliant:	Yes
Fitted To:	Class 373 Eurostar

[3] GPU stands for “Grand Plongeur Unique" (large, single plunger).

Notes:	Captive to HS1 route only, now being withdrawn from service. During the period when Class 373s were running on domestic services North Of London, the NoL class 373 subvariant carried a variant of the GPU pantograph with a UK profile head, and wider suspension points, for compatibility with UK mainline OLE. It also carried modified aerofoils to improve uplift with Mark 3b OLE, and was limited to 110mph on the domestic network.

Faiveley CX PG Monoband Pantograph

Figure C.9: Faiveley CX PG monoband pantograph

Voltage	25kV AC
Use:	High Speed
In UK Since:	2009
Max Speed:	225km/h
Arm:	Single
No. of Strips:	1
Strip Spacing:	N/A
Linkage Type:	External bar links
Suspension:	Primary/secondary
Secondary Suspension Type:	Twin plungers
Secondary Travel:	Unknown
Aerofoils:	On head
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	No – mechanical height limit device provided
Horn Mount:	To fixed head
Horn Type:	Insulated
Head Profile:	HS1 profile
NTSN Compliant:	Yes (level contact wire only)
Fitted To:	Class 395 Javelin
Notes:	Captive to HS1 route only

Faiveley CX NG Pantograph

Figure C.10: Faiveley CX NG pantograph

Voltage	25kV AC
Use:	High Speed
In UK Since:	2016
Max Speed:	360km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	Unknown
Linkage Type:	External bar links
Suspension:	Primary/secondary
Secondary Suspension Type:	Quad plungers
Secondary Travel:	Unknown
Aerofoils:	On head
Strip Material:	Unknown
Auto-Drop Device?	Unknown
Over Height Drop?	No – mechanical height limit device provided
Horn Mount:	To fixed head
Horn Type:	Insulated
Head Profile:	HS1 profile
NTSN Compliant:	Yes
Fitted To:	Class 374 (e320 Eurostar)
Notes:	Captive to HS1 route only

Brecknell Willis High Reach Pantograph

Figure C.11: Brecknell Willis High Reach pantograph

Voltage	750V DC, 1500V DC
Use:	Tram, Metro
In UK Since:	1980
Max Speed:	80km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	Unknown
Linkage Type:	Internal chain (to upper arm), internal bar link (to head)
Suspension:	Primary only (although head mounting strips may provide some minor flex under load)
Secondary Suspension Type:	See above
Secondary Travel:	Negligible
Aerofoils:	None
Strip Material:	Unknown
Auto-Drop Device?	Unknown
Over Height Drop?	Unknown
Horn Mount:	To fixed head
Horn Type:	Live
Head Profile:	1900mm width?
NTSN Compliant:	No
Fitted To:	Trams & Metros: Birmingham Metro T-68 and T-69, Manchester Metrolink T-68A, Tyne & Wear Metro Class 994
Notes:	

Schunk SB Pantograph

Figure C.12: Schunk SB pantograph

Voltage	750V DC
Use:	Tram
In UK Since:	2000
Max Speed:	80km/h
Arm:	Single
No. of Strips:	2
Strip Spacing:	345mm
Linkage Type:	External bar links
Suspension:	Primary/secondary
Secondary Suspension Type:	Flexible support (similar to leaf spring)
Secondary Travel:	Very small
Aerofoils:	None
Strip Material:	Unknown
Auto-Drop Device?	Yes
Over Height Drop?	Unknown
Horn Mount:	To fixed head
Horn Type:	Live
Head Profile:	1900mm width
NTSN Compliant:	No
Fitted To:	ET-Urbos 3, Bham-Urbos 3, Manc-M5000, Croy-Flexity Swift CR4000, Croy-VarioBahn, Nott-Incentro AT6/5, Nott-Alstom Citadis 302, Shef-Siemens-Duewag, Blk-Flexity 2, Dub-Citadis 301, Dub-Citadis 401, Dub-Citadis 402
Notes:	

Blackpool Transport Diamond Pantograph

Figure C.13: Blackpool Transport diamond pantograph

Voltage	600V DC
Use:	Tram
In UK Since:	Early 20th century
Max Speed:	70km/h
Arm:	Two uncrossed diamond
No. of Strips:	2
Strip Spacing:	Unknown
Linkage Type:	Provided by twin arms
Suspension:	Primary only
Secondary Suspension Type:	N/A
Secondary Travel:	None
Aerofoils:	None
Strip Material:	Unknown
Auto-Drop Device?	Assume No
Over Height Drop?	Assume No
Horn Mount:	To fixed head
Horn Type:	Live
Head Profile:	Unknown
NTSN Compliant:	No
Fitted To:	Majority of heritage trams in Blackpool Transport collection
Notes:	These are still in operational service, but only used on special occasions

Appendix D

UK Equipment Types

Type	No.	Designation	Subtype	Suspension	Tensioning	Contact Wire Cross Section (mm²) & Material	Contact Wire Tension @ setup temp (N)	Contact Wire Tension @ setup temp (lb)	Presag?	Catenary Layup & Material	Catenary Tension @ setup temp (N)	Catenary Tension @ setup temp (lb)	Auxiliary Catenary or Stitch Wire Layup & Material	Auxiliary Tension @ setup temp (N)	Auxiliary Tension @ setup temp (lb)	System Height	Linespeed (mph)	Linespeed (kph)	TSI Compliant?
Shenfield - Chelmsford - Southend (SCS)	1	SCS 00-FT-C	Orig. ML Compound FT[2]	Compound	FT	193 CuCd	13340	3000	No	37/2.4 HDCu ¢	13880	3120	19/2.1 CuCd (was HDCu)	5355	1203	2057	80	128	No
	2	SCS 00-FT-S	Orig. RML Simple FT	Simple	FT	193 CuCd	13340	3000	No	37/2.4 HDCu	12140	2730	-	-	-		50	80	
	3	SCS 01-FT-S	Orig. Sidings Simple FT	Simple	FT	107 CuCd	7560	1700	No	19/2.1 CuCd (was HDCu)	6070	1365	-	-	-		45	72	
	4	SCS 02-FT(2)-S	Orig. reduced tension Simple FT (1 x heavy equipment splits into 2 x light)	Simple	FT	193 CuCd	13340	3000	No	37/2.4 HDCu	12140	2730	-	-	-		45	72	
		SCS 02-FT(2)-S	Orig. reduced tension Simple FT (1 x heavy equipment splits into 2 x light)	Simple	FT	2x107 CuCd	2x6670	2x1500		2x19/2.1 CuCd	2x6075	2x1365	-	-	-				
	5	SCS 03-AT-C	ML Compound AT[2]	Compound	AT	193 CuCd	13340	3000	No	37/2.4 HDCu ¢	13880	3120	19/2.1 CuCd (was HDCu)	5350	1203		80	128	
	6	?	SCS Tramway	Tramway	?	?	?	?	N/A	-	-	-	-	-	-	-	?	?	
Great Eastern (GE) & Manchester - Wath - Sheffield (MSW)[1]	7	GE/MSW-00-FT-C	Original ML Compound FT	Compound	FT	193 CuCd	13340	3000	No	37/2.64 HDCu	16950	3810	19/2.85 HDCu	5670	1275	1638	80	128	No
	8	GE/MSW-04-FT-T	Original Tramway FT	Tramway	FT	193 CuCd	13340	3000	N/A	-	-	-	-	-	-	-	25	40	
	9	GE-00-FT-S	Original RML Simple FT	Simple	FT	193 CuCd	13340	3000	No	37/2.64 HDCu	16950	3810	-	-	-		50	80	
	10	GE-01-FT-S	Original Sidings Simple FT	Simple	FT	193 CuCd	13340	3000	No	7/3.63 CuCd	8840	1988	-	-	-		40	64	
	11	GE-03-FT(2)-S	Reduced tension Simple FT (1 x heavy equipment splits into 2 x light)	Simple	FT	193 CuCd	13340	3000	No	37/2.64 HDCu	16950	3810	-	-	-	1638	40	64	
		GE-03-FT(2)-S	Reduced tension Simple FT (1 x heavy equipment splits into 2 x light)	Simple	FT	2x107 CuCd	2x6675	2x1500	N/A	2x19/2.1 CuCd	2x1905	2x8470	-	-	-				
	12	GE-03-FT(2)-T	Reduced tension Tramway FT (1 x heavy equipment splits into 2 x light)	Tramway	FT	193 CuCd	13340	3000	N/A	-	-	-	-	-	-	-	25	40	
		GE-03-FT(2)-T	Reduced tension Tramway FT (1 x heavy equipment splits into 2 x light)	Tramway		2x107 CuCd	2x6675	2x1500	N/A	-	-	-	-	-	-				
	13	GE-06-FCA-S	RML(heavy) Simple semi-AT	Simple	FT cat, AT cw	193 CuCd	13340	3000	No	37/2.64 HDCu	13760	3092	-	-	-	1638	97	155	
	14	GE-07?	RML(light) Simple FT?	Simple	FT	193 CuCd	13350	3000	No	?	10280	2310	-	-	-		40	64	
	15	MSW-02-FT-S	Original RML(light) Simple FT	Simple	FT	193 CuCd	13340	3000	No	19/2.85 HDCu	14460	3250	-	-	-		40	64	
	16	MSW-05-FCO(SP)-S	Original RML(heavy) Simple semi-AT (spring tensioned)	Simple	AT cat FT cw	193 CuCd	13340	3000	No	37/2.64 HDCu	16950	3810	-	-	-	1753	80	128	

Type	No.	Designation	Subtype	Suspension	Tensioning	Contact Wire Cross Section (mm²) & Material	Contact Wire Tension @ setup temp (N)	Contact Wire Tension @ setup temp (lb)	Presag?	Catenary Layup & Material	Catenary Tension @ setup temp (N)	Catenary Tension @ setup temp (lb)	Auxiliary Catenary or Stitch Wire Layup & Material	Auxiliary Tension @ setup temp (N)	Auxiliary Tension @ setup temp (lb)	System Height	Linespeed (mph)	Linespeed (kph)	TSI Compliant?
Mark 1	17	Mk 1-00-AT-C	Compound AT	Compound	AT	107 CuCd	8918	2000	No	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675	1980	110	175	No
	18	Mk 1-00-AT-S	Simple AT	Simple	AT	107 CuCd	8918	2000	No	19/2.1 CuCd	8195	1838	-	-	-		80	128	
	17	Mk 1-00-FT-S	Simple FT	Simple	FT	107 CuCd	9921	2225	No	19/2.1 CuCd	8195	1838	-	-	-		60	95	
	19	Mk 1-00-FT-T	Tramway FT	Tramway	FT	107 CuCd	11326	2540	N/A	-	-	-	-	-	-		25	40	
	18	Mk 1-00-FCO-S	Simple Fixed Contact Wire, Auto Catenary	Simple	AT cat, FT cw	107 CuCd	8829	1980	No	19/2.1 CuCd	8195	1838	-	-	-		?	?	
	20	Mk 1-01-AT-C	Biased compound AT	Compound	AT	107 CuCd	8918	2000	No	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675		110	175	
	19	Mk 1-01-AT-S	Sagged Simple AT	Sagged Simple	AT	107 CuCd	8918	2000	Yes	19/2.1 CuCd	8195	1838	-	-	-		80	128	
	21	Mk 1-02-AT-C	Biased compound AT (supertensioned)	Compound	AT	107 CuCd	11300	2540	No	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675		110	175	
	20	Mk 1-02-AT-S	Simple AT (supertensioned)	Simple	AT	107 CuCd	11300	2540	No	19/2.1 CuCd	8195	1838	-	-	-		80	128	
	22	Mk 1-03-AT-C	Sagged biased compound AT (supertensioned)	Compound	AT	107 CuCd	11300	2540	Yes	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675		110	175	
	21	Mk 1-03-AT-S	Sagged biased simple AT (supertensioned)	Simple	AT	107 CuCd	11147	2500	Yes	19/2.1 CuCd	11147	2500	-	-	-		110	175	
	23	Mk 1-04-AT-C	Sagged compound AT	Compound	AT	107 CuCd	8918	2000	Yes	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675		110	175	
	22	Mk 1-05-AT-C	Sagged compound AT (supertensioned)	Compound	AT	107 CuCd	11300	2540	Yes	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675		110	175	
	24	Mk 1-06-AT-C	Sagged biased compound AT	Compound	AT	107 CuCd	8918	2000	Yes	19/2.1 CuCd	8584	1925	7/2.1 CuCd	3000	675		110	175	
	23	N/A	Sagged Simple AT UK1 upgrade (for 200kph)	Sagged Simple	AT	120 CuAg	11900	2674	Yes	19/2.1 CuCd	8560	1923	-	-	-		125	200	
	24	N/A	Sagged Simple AT UK1 upgrade (for 225kph)	Sagged Simple	AT	120 CuAg	14000	3146	Yes	19/2.1 CuCd	8560	1923	-	-	-		140	225	
	25	UKMS-R1L(CuAg)	Sagged Simple AT UKMS upgrade (for 80mph)	Sagged Simple	AT	107 CuAg	8918	2004	Yes	19/2.1 BzII	8195	1842	-	-	-		80	130	
	26	UKMS-R1S(CuAg)	Sagged Simple AT UKMS upgrade (for 100mph)	Sagged Simple	AT	107 CuAg	11300	2540	Yes	19/2.1 BzII	8195	1842	-	-	-		100	160	
	27	UKMS-R1L(CuSn)	Sagged Simple AT UKMS upgrade (for 80mph)	Sagged Simple	AT	107 CuSn	8918	2004	Yes	19/2.1 BzII	8195	1842	-	-	-		80	130	Yes
	28	UKMS-R1S(CuSn)	Sagged Simple AT UKMS upgrade (for 100mph)	Sagged Simple	AT	107 CuSn	11300	2540	Yes	19/2.1 BzII	8195	1842	-	-	-		100	160	
	-	N/A	Stitched Simple AT	Stitched Simple	AT	CuCd	8900	2000	No	CuCd	8195	1838	CuCd	1510	339		80	128	No
Brown Boveri	29	Mk BBC-00	Sagged Stitched Simple AT	Sagged Stitched Simple	AT	107 CuCd	8918	2000	Yes	19/2.1 CuCd	8195	1838	7/2.1 CuCd	1957	440	?	100	160	No
Mark 2	-	Mk 2-00-AT-C	Compound AT	Compound	AT	107 CuCd	8918	2000	No	19/2.1 CuCd	8918	2000	7/2.1 CuCd	3000	675	?	110	175	No
	30	Mk 2-00-AT-S	Simple AT	Simple	AT	107 HDCu	8918	2000	No	19/2.1 HDCu	8195	1838	-	-	-	?	75	120	
	31	Mk 2-00-FT-S	Simple FT	Simple	FT	107 CuCd	9921	2225	No	19/2.1 HDCu	8195	1838	-	-	-	?	60	96	
	32	Mk 2-00-FT-T	Tramway FT	Tramway	FT	107 CuCd	9921	2225	N/A	-	-	-	-	-	-	N/A	25	40	
	33	Mk 2-01-AT-S	Sagged Simple AT	Sagged Simple	AT	107 HDCu	8918	2000	Yes	19/2.1 HDCu	8195	1838	-	-	-	?	100	160	
	34	Mk 2-02-AT-S	Sagged Simple AT (supertensioned)	Sagged Simple	AT	107 HDCu	11147	2500	Yes	19/2.1 HDCu	8195	1838	-	-	-	?	100	160	
Mark 3	35	?	Sagged Simple AT	Sagged Simple	AT	107 HDCu	8925	2005	Yes	19/2.1 HDCu	11100	2494	-	-	-	1400	110	175	No
	36	?	Simple FT	Simple	FT	107 CuCd	11180	2512		19/2.1 HDCu	8630	1939	-	-	-		64	100	
	37	?	Tramway	Tramway	FT?	107 CuCd?	11180	2512	N/A	-	-	-	-	-	-	-	20	30	
Mark 3a	38	Mk 3A-00-AT-S	Sagged Simple AT	Sagged Simple	AT	107 HDCu	8930	2006	Yes	5/2/3.95 AWAC	11000	2472	-	-	-	1400	110	175	No
	39	Mk 3A-00-FT-S	Simple FT	Simple	FT	107 CuCd	11180	2512	No	5/2/3.95 AWAC	8630	1939	-	-	-		60	95	
	40	Mk 3A-00-AT-T	Tramway AT	Tramway	AT	107 HDCu	8930	2006	N/A	-	-	-	-	-	-		?	?	
	41	Mk 3A-00-FT-T	Tramway FT	Tramway	FT	107 CuCd	11180	2512	N/A	-	-	-	-	-	-		18	30	
	42	Mk 3A-00-FT/T	Simple FT (1 x simple equipment splits into 2 x tramway)	Simple	FT	107 CuCd	11180	2512	No	5/2/3.95 AWAC	8630	1939	-	-	-		?	?	
		Mk 3A-00-FT/T	Simple FT (1 x simple equipment splits into 2 x tramway)	Tramway	FT	2x107 CuCd	2x11180	2x2512	N/A	-	-	-	-	-	-		?	?	
	43	Mk 3A-01-AT-S	Sagged Simple AT (Mk3b tensions)	Sagged Simple	AT	107 HDCu	11000	2472	Yes	5/2/3.95 AWAC	11000	2472	-	-	-		110	175	
	44	Mk 3A-02-AT-S	Sagged Simple AT (supertensioned)	Sagged Simple	AT	107 HDCu	11160	2507	Yes	5/2/3.95 AWAC	11160	2507	-	-	-		125	200	
	45	Mk 3A-03-AT-S	Sagged Stitched Simple AT	Sagged Stitched Simple	AT	107 HDCu	11000	2472	Yes	5/2/3.95 AWAC	11000	2472	4mm Stainless Steel	2250	505		125	200	
	46	Mk 3A-04-AT-TW	Tramway AT	Tramway	AT	107 HDCu	11910	2676	N/A	-	-	-	-	-	-		60	95	
	47	N/A	Sagged Simple AT UK1 upgrade (for 200kph)	Sagged Simple	AT	120 CuAg	11900	2674	Yes	19/2.1 CuCd	8560	1923	-	-	-		125	200	
	48	N/A	Sagged Simple AT UK1 upgrade (for 225kph)	Sagged Simple	AT	120 CuAg	11900	2674	Yes	19/2.1 CuCd	8560	1923	-	-	-		140	225	

Type	No.	Designation	Subtype	Suspension	Tensioning	Contact Wire Cross Section (mm²) & Material	Contact Wire Tension @ setup temp (N)	Contact Wire Tension @ setup temp (lb)	Presag?	Catenary Layup & Material	Catenary Tension @ setup temp (N)	Catenary Tension @ setup temp (lb)	Auxiliary Catenary or Stitch Wire Layup & Material	Auxiliary Tension @ setup temp (N)	Auxiliary Tension @ setup temp (lb)	System Height	Linespeed (mph)	Linespeed (kph)	TSI Compliant?
Mark 3b	49	Mk 3B-01-AT-S	Sagged Simple AT	Sagged Simple	AT	107 HDCu	11000	2472	Yes	5/2/3.95 AWAC	11000	2472	-	-	-	900/1400[3]	125	200	No
	50	Mk 3B-00-FT-S	Simple FT	Simple	FT	107 CuCd	11180	2512	No	5/2/3.95 AWAC	8630	1939	-	-	-	1400	60	95	
	51	Mk 3B-00-AT-T	Tramway AT	Tramway	AT	107 HDCu	11000	2472	N/A	-	-	-	-	-	-	-	25	40	
	52	Mk 3B-00-FT-T	Tramway FT	Tramway	FT	107 CuCd	11180	2512	N/A	-	-	-	-	-	-	-	25	40	
Mark 3c	53	Mk 3C-00-AT-S	Sagged Simple AT	Sagged Simple	AT	107 HDCu	11000	2472	Yes	19/2.1 HDCu	11000	2472	-	-	-	900/1400[3]	125	200	No
	54	Mk 3C-00-FT-S	Simple FT	Simple	FT	107 CuCd	11180	2512	No	19/2.1 CuCd	8630	1939	-	-	-	900/1400[3]	60	95	
Mark 3d	55	N/A	Sagged Simple AT	Sagged Simple	AT	107 CuSn (0.4)	11000	2472	Yes	19/2.1 Bz	11000	2472	-	-	-	900/1400[3]	125	200	No
	56	N/A	Sagged Simple AT (modified)	Sagged Simple	AT	107 Cu-Mg	11000	2472	Yes	19/2.1 Bz	11000	2472	-	-	-	900/1400[3]	?	?	
	57	N/A	Simple FT	Simple	FT	107 CuSn (0.4)	?	?	No	19/2.1 Bz	?	?	-	-	-	?	?	?	
Mark 4	-	N/A	Compound AT	Compound	AT	107 CuCd	18000	4045	Yes	19/3.39 AWAC	24000	5393	19/3.39 AWAC	11000	2472	900/1400[3]	155	245	No
Mark 5	58	Mk 5-00-AT-S	Simple AT	Simple	AT	150 HDCu	20200	4539	Yes	37/2.5 HDCu	20720	4656	-	-	-	?	100	160	No
Channel Tunnel	59	N/A	Sagged? Simple AT	Sagged? Simple	AT	?	?	?	Yes?	?	?	?	-	-	-	?	100	160	No
Heathrow Tunnel	60	N/A	Simple AT	Simple	AT	107 HDCu	11000	2472	No	5/2/3.95 AWAC	11000	2472	-	-	-	180	80	128	No
UK1 standalone	61	N/A	Sagged Simple AT (for 200kph)	Sagged Simple	AT	120 CuAg	11900	2674	Yes	19/2.1 CuCd	8560	1923	-	-	-	?	125	200	No
	62	N/A	Sagged Simple AT (for 225kph)	Sagged Simple	AT	120 CuAg	14000	3146	Yes	19/2.1 CuCd	8560	1923	-	-	-	?	140	225	
High Speed One	63	N/A	Sagged Simple AT	Sagged Simple	AT	150 HDCu	20000	4494	Yes	37/1.5 Bz	14000	3146	-	-	-	1400	189	300	No
High Speed Two	-	SNCF Réseau V360	V360 high speed	Sagged Simple	AT	150 CuSn	27500	6182	Yes	19/2.1 BzII	14000	3146	-	-	-	1400	360	575	Yes
	-	SNCF Réseau V360	V360 low speed	Sagged Simple	AT	150 CuSn	14000	3146	Yes	19/2.1 BzII	14000	3146	-	-	-	?	230	370	
SICAT	64	SICAT SA	Simple AT	Simple	AT	107 CuAg	11230	2523	No	19/2.1 BzII	11230	2523	-	-	-	1200	100	160	No
	65	SICAT SA (Mk2 tension)	Simple AT	Simple	AT	107 CuAg	8915	2003	No	19/2.1 BzII	8915	2003	-	-	-	1200	100	160	
GEFF	66	N/A	Sagged Simple AT	Sagged Simple	AT	120 CuAg	13200	2966	Yes	19/2.1 BzII	12000	2696	-	-	-	-	100	160	No
	67	N/A	Sagged Simple AT	Sagged Simple	AT	120 CuAg	7500	1685	Yes	19/2.1 BzII	10000	2247	-	-	-	-	60	100	
Series 1	68	N/A	Sagged Simple AT	Sagged Simple	AT	120 CuAg	16500	3708	Yes	19/2.1 BzII	13000	2921	-	-	-	-	140	225	Yes
Series 2	69	Series 2(120)	Sagged Simple AT	Sagged Simple	AT	120 CuAg	14000	3146	Yes	19/2.1 BzII	12000	2696	-	-	-	1300	100	160	Yes
	70	Series 2(107CuAg)	Sagged Simple AT	Sagged Simple	AT	107 CuAg	11000	2472	Yes	19/2.1 BzII	11000	2472	-	-	-	1300	100	160	
	71	Series 2(107CuSn)	Sagged Simple AT	Sagged Simple	AT	107 CuSn	11000	2472	Yes	19/2.1 BzII	11000	2472	-	-	-	1300	100	160	
	72	Series 2(FT)	Sagged Simple FT	Sagged Simple	FT	107 CuAg	11000	2472	Yes	19/2.1 BzII	11000	2472	-	-	-	1300	60	100	
UK Master Series	73	UKMS100	Sagged Simple AT	Sagged Simple	AT	107 CuAg	11000	2472	Yes	19/2.1 BzII	11000	2472	-	-	-	1300	100	160	Yes
	74	UKMS100-Sn	Sagged Simple AT	Sagged Simple	AT	107 CuSn	11000	2472	Yes	19/2.1 BzII	11000	2472	-	-	-	1300	100	160	
	75	UKMS125	Sagged Simple AT	Sagged Simple	AT	120 CuAg	15000	3372	Yes	19/2.1 BzII	12000	2696	-	-	-	1300	125	200	
	76	UKMS140	Sagged Simple AT	Sagged Simple	AT	120 CuAg	16500	3708	Yes	19/2.1 BzII	13000	2921	-	-	-	1300	140	225	
F+F ROCS	77	ROCS (120 CuAg)	Rigid Overhead Conductor Bar	N/A	None	120 CuAg	0	0	No	-	-	-	-	-	-	-	?	?	Yes
	78	ROCS (150 AlSiMg)	Rigid Overhead Conductor Bar	N/A	None	150 AlSiMg	0	0	No	-	-	-	-	-	-	-	70	113	
Alstom Cariboni ROCS	79	N/A	Rigid Overhead Conductor Bar	N/A	None	150 HDCu?	0	0	No	-	-	-	-	-	-	-	?	?	Yes
Alstom Cariboni	80	N/A	Sagged Simple AT (heavy catenary)	Sagged Simple	AT	150 HDCu	12000	2696	Yes	37/1.5 BzII	12000	2696	-	-	-	?	60	100	Yes
	81	N/A	Sagged Simple AT (light catenary)	Sagged Simple	AT	150 HDCu	12000	2696	Yes	19/2.1 BzII	12000	2696	-	-	-	?	?	?	
Tyne & Wear Metro	82	T&W Simple AT (CuAg)	Simple AT	Simple	AT	107 CuAg	11000	2472	No	19/2.1 HDCu	11000	2472	-	-	-	900	62	100	No
	83	T&W Simple AT (CuCd)	Simple AT	Simple	AT	107 CuCd	11000	2472	No	19/2.1 HDCu	11000	2472	-	-	-				
	84	T&W Tramway AT	Tramway	Tramway	AT?	107 CuAg	11000?	2472?	N/A	-	-	-	-	-	-	-			
	85	T&W 1 CW +2 Caty AT	Simple AT	Simple	AT?	107 CuAg	11000?	2472?	No	2 x 19/2.1 HDCu	2x11000?	2x2472?	-	-	-				
	86	T&W 2 CW +2 Caty AT	Simple AT	Simple	AT	2x107 CuAg	2x11000?	2x2472?	No	2 x 19/2.1 HDCu	2x11000?	2x2472?	-	-	-				
	87	T&W 2 CW +2 Caty FT	Simple FT	Simple	FT	2x107 CuAg	2x11000?	2x2472?	No	2 x 19/2.1 HDCu	2x11000?	2x2472?	-	-	-				
	88	T&W 2 CW +1 Caty AT	Simple AT	Simple	AT	2x107 Cu-??	?	?	No	?	?	?	-	-	-				
	89	T&W Simple AT (CuCd)	Simple FT	Simple	FT	107 CuAg	11000	2472	No	19/2.1 HDCu	11000	2472	-	-	-				
	90	T&W Siemens	Simple AT	Simple	AT	?	?	?	No	?	?	?	-	-	-	?			
	91	T&W FL200 Light	Simple AT	Simple	AT	107 Cu-??	11000	2472	No	19/3.2 Cu-??	11000	2472	-	-	-	900			

Type	No.	Designation	Subtype	Suspension	Tensioning	Contact Wire Cross Section (mm²) & Material	Contact Wire Tension @ setup temp (N)	Contact Wire Tension @ setup temp (lb)	Presag?	Catenary Layup & Material	Catenary Tension @ setup temp (N)	Catenary Tension @ setup temp (lb)	Auxiliary Catenary or Stitch Wire Layup & Material	Auxiliary Tension @ setup temp (N)	Auxiliary Tension @ setup temp (lb)	System Height	Linespeed (mph)	Linespeed (kph)	TSI Compliant?
Croydon	92	N/A	Tramway AT (double CW)	Tramway	AT	twin	?	?	N/A	-	-	-	-	-	-	-	50	80	No
Tramlink	93	N/A	Tramway AT (single CW)	Tramway	AT	single	?	?	N/A	-	-	-	-	-	-	-	50	80	
Midland Metro	94	N/A	Tramway FT? AT?	Tramway	?	?	?	?	?	?	?	?	-	-	-	-	45	70	No
Manchester Metrolink	95	N/A	Simple AT	Simple	AT	120 HDCu	12000	2696	No	2 x 19/2.8 HDCu	12000	2696	-	-	-	?	50	80	No
	96	N/A	MJSA (Mark 3 Simple FT converted from Mark 1)	Simple	FT	107 CuCd	12092	2717	No	19/2.1 HDCu	8612	1935	-	-	-	1400	64	100	
	97	N/A	Tramway FT Reduced Tension	Tramway	FT	2 x 120 CuCd	12000	2696	N/A	-	-	-	-	-	-	-	30	45	
	98	N/A	Tramway FT	Tramway	FT	2 x 120 CuCd	24000	5393	N/A	-	-	-	-	-	-	-	30	45	
Sheffield Supertram	99	N/A	Tramway FT? AT?	Tramway	?	107 Cu-??	?	?	No	-	-	-	-	-	-	-	?	?	No
Nottingham Express Transit	100	N/A	Tramway	Tramway	?	?	?	?	N/A	-	-	-	-	-	-	-	?	?	No
	101	N/A	Simple	Simple	?	?	?	?	No	?	?	?	-	-	-	?	50	80	
Blackpool Tram	102	N/A	Tramway FT?	Tramway	?	?	?	?	N/A	-	-	-	-	-	-	-	?	?	No
Luas Tram	103	N/A	Tramway AT	Tramway	AT	120 HDCu	12000	2696	N/A	-	-	-	-	-	-	-	45	70	No
	104	N/A	Tramway FT	Tramway	FT	120 HDCu	12000	2696	N/A	-	-	-	-	-	-	-	?	?	
Edinburgh Tram	105	N/A	Tramway AT	Tramway	AT	120 CuAg	12000	2696	N/A	-	-	-	-	-	-	-	?	?	No
	106	N/A	Simple AT	Simple	AT	120 CuAg	12000	2696	N/A	120mm^2	12000	2696	-	-	-	?	?	?	
Sheffield Tram-Train	107	Series 2(120) DC conversion	Sagged Simple AT	Sagged Simple?	AT	120 CuAg	14000	3146	Yes	19/2.1 BzII	12000	2696	-	-	-	1400	?	?	No

No.	Designation	Subtype	Designer	Build Date	Build Voltage	Conversion Date	Conversion Voltage	Conversion Date2	Conversion Voltage3	Country / Administration	Locations
1	SCS 00-FT-C	Orig. ML Compound FT[2]	BICC	1956	1500V DC	1960 - 1962	6.25kV AC	1979	25kV AC	UK / NR	Shenfield - Witham; Shenfield - Southend
2	SCS 00-FT-S	Orig. RML Simple FT									
3	SCS 01-FT-S	Orig. Sidings Simple FT									
4	SCS 02-FT(2)-S	Orig. reduced tension Simple FT (1 x heavy equipment splits into 2 x light)									
	SCS 02-FT(2)-S	Orig. reduced tension Simple FT (1 x heavy equipment splits into 2 x light)									
5	SCS 03-AT-C	ML Compound AT[2]									
6	?	SCS Tramway									
7	GE/MSW-00-FT-C	Original ML Compound FT	BICC	1949 (GE) 1952 (MSW)	1500V DC	1960 (GE only)	6.25kV AC	1976 - 1987 (GE) 1984 (MSW)	25kV AC	UK / NR	Liverpool St - Shenfield; Christian St Jct - Gas Factory Jct; Manchester - Sheffield (via Wath - now curtailed to Ardwick - Hadfield)
8	GE/MSW-04-FT-T	Original Tramway FT									
9	GE-00-FT-S	Original RML Simple FT									
10	GE-01-FT-S	Original Sidings Simple FT									
11	GE-03-FT(2)-S	Reduced tension Simple FT (1 x heavy equipment splits into 2 x light)									
	GE-03-FT(2)-S	Reduced tension Simple FT (1 x heavy equipment splits into 2 x light)									
12	GE-03-FT(2)-T	Reduced tension Tramway FT (1 x heavy equipment splits into 2 x light)									Liverpool St - Shenfield; Christian St Jct - Gas Factory Jct;
	GE-03-FT(2)-T	Reduced tension Tramway FT (1 x heavy equipment splits into 2 x light)									
13	GE-06-FCA-S	RML(heavy) Simple semi-AT									
14	GE-07?	RML(light) Simple FT?									Gas Factory Jct - Bow Jct
15	MSW-02-FT-S	Original RML(light) Simple FT									
16	MSW-05-FCO(SP)-S	Original RML(heavy) Simple semi-AT (spring tensioned)									Manchester - Sheffield (via Wath - now curtailed to Ardwick - Hadfield)

No.	Designation	Subtype	Designer	Build Date	Build Voltage	Conversion Date	Conversion Voltage	Conversion Date2	Conversion Voltage3	Country / Administration	Locations
17	Mk 1-00-AT-C	Compound AT									
18	Mk 1-00-AT-S	Simple AT		1957							
17	Mk 1-00-FT-S	Simple FT									
19	Mk 1-00-FT-T	Tramway FT									
18	Mk 1-00-FCO-S	Simple Fixed Contact Wire, Auto Catenary									
20	Mk 1-01-AT-C	Biased compound AT		?							
19	Mk 1-01-AT-S	Sagged Simple AT	BICC	?							
21	Mk 1-02-AT-C	Biased compound AT (supertensioned)		?							
20	Mk 1-02-AT-S	Simple AT (supertensioned)		?	25kV AC	-	-	-	-	UK / NR	London Euston - Weaver Jct; Crewe - Liverpool; Colwich - Manchester; Crewe - Manchester; Rugby - Stafford via Birmingham; Roade - Rugby via Northampton; Glasgow suburban stage 1; Christian St Jct - Shoeburyness; Barking - Pitsea via Grays; Chelmsford - Colchester; Colchester - Clacton & Walton; Bethnal Green - Bishop's Stortford, Hertford East, Enfield & Chingford;
22	Mk 1-03-AT-C	Sagged biased compound AT (supertensioned)		?							
21	Mk 1-03-AT-S	Sagged biased simple AT (supertensioned)		?							
23	Mk 1-04-AT-C	Sagged compound AT		?							
22	Mk 1-05-AT-C	Sagged compound AT (supertensioned)		?							
24	Mk 1-06-AT-C	Sagged biased compound AT		?							
23	N/A	Sagged Simple AT UK1 upgrade (for 200kph)	Balfour Beatty/WS	2000							
24	N/A	Sagged Simple AT UK1 upgrade (for 225kph)	Atkins	not used							
25	UKMS-R1L(CuAg)	Sagged Simple AT UKMS upgrade (for 80mph)									
26	UKMS-R1S(CuAg)	Sagged Simple AT UKMS upgrade (for 100mph)	Network Rail	2019							Mark 1 upgrade locations in East Anglia
27	UKMS-R1L(CuSn)	Sagged Simple AT UKMS upgrade (for 80mph)									
28	UKMS-R1S(CuSn)	Sagged Simple AT UKMS upgrade (for 100mph)									
-	N/A	Stitched Simple AT	BICC	1957							All installed equipment now removed
29	Mk BBC-00	Sagged Stitched Simple AT	Brown Boveri	1961	6.25kV AC	1979	25kV AC	-	-	UK / NR	Whitecraigs - Neilston
-	Mk 2-00-AT-C	Compound AT									Manchester - Crewe via Styal (now removed)
30	Mk 2-00-AT-S	Simple AT									
31	Mk 2-00-FT-S	Simple FT	BICC	1966	25kV AC	-	-	-	-	UK / NR	Glasgow - Wemyss Bay; Glasgow - Gourock (Glasgow suburban stage 2)
32	Mk 2-00-FT-T	Tramway FT									
33	Mk 2-01-AT-S	Sagged Simple AT									
34	Mk 2-02-AT-S	Sagged Simple AT (supertensioned)									
35	?	Sagged Simple AT									
36	?	Simple FT	British Rail/BICC	1968	25kV AC	-	-	-	-	UK / NR	Clapton - Cheshunt (Lea Valley)
37	?	Tramway									
38	Mk 3A-00-AT-S	Sagged Simple AT									
39	Mk 3A-00-FT-S	Simple FT									
40	Mk 3A-00-AT-T	Tramway AT									
41	Mk 3A-00-FT-T	Tramway FT									
42	Mk 3A-00-FT/T	Simple FT (1 x simple equipment splits into 2 x tramway)									
	Mk 3A-00-FT/T	Simple FT (1 x simple equipment splits into 2 x tramway)	British Rail/BICC	1972	25kV AC	-	-	-	-	UK / NR	Weaver Jct - Glasgow; King's Cross - Royston & Hertford Loop; Witham - Braintree
43	Mk 3A-01-AT-S	Sagged Simple AT (Mk3b tensions)									
44	Mk 3A-02-AT-S	Sagged Simple AT (supertensioned)									
45	Mk 3A-03-AT-S	Sagged Stitched Simple AT									
46	Mk 3A-04-AT-TW	Tramway AT									King's Lynn sidings
47	N/A	Sagged Simple AT UK1 upgrade (for 200kph)		2000							Weaver Jct - Glasgow
48	N/A	Sagged Simple AT UK1 upgrade (for 225kph)		not used							

No.	Designation	Subtype	Designer	Build Date	Build Voltage	Conversion Date	Conversion Voltage	Conversion Date2	Conversion Voltage3	Country / Administration	Locations
49	Mk 3B-01-AT-S	Sagged Simple AT	British Rail	1978	25kV AC	-	-	-	-	UK / NR	St Pancras - Bedford; Hitchin - Edinburgh; Doncaster - Leeds; Leeds - Ilkley, Skipton & Bradford; Carstairs - Edinburgh; Bishop's Stortford - King's Lynn, Royston & Stansted; Colchester - Norwich & Harwich; Romford - Upminster; Wickford - Southminster; Paisley - Ayr & Largs; West London Line
50	Mk 3B-00-FT-S	Simple FT									
51	Mk 3B-00-AT-T	Tramway AT									
52	Mk 3B-00-FT-T	Tramway FT									
53	Mk 3C-00-AT-S	Sagged Simple AT	British Rail	1980	25kV AC	-	-	-	-	UK / NR	Stockport - Hazel Grove; London Fenchurch St - Christian St Jct
54	Mk 3C-00-FT-S	Simple FT									
55	N/A	Sagged Simple AT	Network Rail	2005	25kV AC	-	-	-	-	UK / NR	Various locations on ECML
56	N/A	Sagged Simple AT (modified)		2010							Airdrie to Haymarket via Armadale and Bathgate
57	N/A	Simple FT		2015							Thameslink Tunnel (1 tension length)
-	N/A	Compound AT	Balfour Beatty	not used	25kV AC	-	-	-	-	UK / NR	Not installed (developed for West Coast upgrade for APT)
58	Mk 5-00-AT-S	Simple AT	British Rail	1992	25kV AC	-	-	-	-	UK / NR	Dollands Moor Yard
59	N/A	Sagged? Simple AT	Balfour Beatty	1994	25kV AC	-	-	-	-	UK/France	Cheriton - Frethun (France)
60	N/A	Simple AT	British Rail	1996	25kV AC	-	-	-	-	UK / BAA	Stockley Airport Junction - Heathrow Terminals
61	N/A	Sagged Simple AT (for 200kph)	Balfour Beatty/WS Atkins	2003	25kV AC	-	-	-	-	UK / NR	Crewe - Kidsgrove; Old Dalby Test Track
62	N/A	Sagged Simple AT (for 225kph)		-		-	-	-	-		Not installed
63	N/A	Sagged Simple AT	Amec Spie	2003	±25kV AC	-	-	-	-	UK / NR	Fawkenham Jct - St Pancras International
-	SNCF Réseau V360	V360 high speed	SNCF Réseau	TBC	±25kV AC	-	-	-	-	UK / HS2	Euston to Birmingham (HS2)
-	SNCF Réseau V360	V360 low speed									
64	SICAT SA	Simple AT	Siemens	2005	25kV AC	-	-	-	-	UK	Haughhead - Larkhall
65	SICAT SA (Mk2 tension)	Simple AT		2005							Shields - Gourock
66	N/A	Sagged Simple AT	Network Rail/Furrer+Frey	2008	25kV AC	-	-	-	-	UK / NR	London Liverpool St - Shenfield
67	N/A	Sagged Simple AT									Pudding Mill Lane (Crossrail)
68	N/A	Sagged Simple AT	Network Rail/Furrer+Frey	2015	25kV AC	-	-	-	-	UK / NR	Stockley Airport Junction - Reading - Didcot - Bristol Parkway - Cardiff; Reading - Newbury; Wootton Bassett - Chippenham
69	Series 2(120)	Sagged Simple AT	Network Rail	2014	25kV AC	-	-	-	-	UK / NR	Glasgow Queen St Tunnel - Newbridge; Larbert - Stirling;
70	Series 2(107CuAg)	Sagged Simple AT		-							Not used
71	Series 2(107CuSn)	Sagged Simple AT		2012							Manchester Victoria - Edge Hill; Manchester - Preston - Blackpool; Rutherglen - Coatbridge; Cowlairs - Cumbernauld - Greenhill; Greenhill - Larbert; Polmont to Larbert; Stirling - Dunblane - Alloa; Gospel Oak - Barking; Midcalder Jct - Holytown Junction via Shotts; Walsall - Rugeley; Tinsley Viaduct - Rotherham
72	Series 2(FT)	Sagged Simple FT		2017							Glasgow Queen St
73	UKMS100	Sagged Simple AT	Network Rail	2017	25kV AC	-	-	-	-	UK / NR	Bedford - Kettering - Corby
74	UKMS100-Sn	Sagged Simple AT									
75	UKMS125	Sagged Simple AT									
76	UKMS140	Sagged Simple AT		not used[4]							Not used[4]
77	ROCS (120 CuAg)	Rigid Overhead Conductor Bar	Network Rail/Furrer+Frey	2017	25kV AC	-	-	-	-	UK / NR	Chipping Sodbury Tunnel
78	ROCS (150 AlSiMg)	Rigid Overhead Conductor Bar		2019							Severn Tunnel
79	N/A	Rigid Overhead Conductor Bar	Crossrail / Alstom	2016	25kV AC	-	-	-	-	UK / Crossrail	Pudding Mill Lane - Paddington
80	N/A	Sagged Simple AT (heavy catenary)	Alstom	2017	25kV AC	-	-	-	-	UK / Crossrail	Royal Oak Tunnel portal - Westbourne Park
81	N/A	Sagged Simple AT (light catenary)									Custom House - Abbey Wood (surface sections)
82	T&W Simple AT (CuAg)	Simple AT	Adtranz	1980	1500V DC	-	-	-	-	UK / NR	Tyne & Wear Metro North Tyneside Loop and South Tyneside branch; St James to South Shields; South Gosforth - Airport
83	T&W Simple AT (CuCd)	Simple AT									
84	T&W Tramway AT	Tramway									
85	T&W 1 CW +2 Caty AT	Simple AT									
86	T&W 2 CW +2 Caty AT	Simple AT									
87	T&W 2 CW +2 Caty FT	Simple FT									
88	T&W 2 CW +1 Caty AT	Simple AT									
89	T&W Simple AT (CuCd)	Simple FT									
90	T&W Siemens	Simple AT	Siemens	2002							Tyne & Wear Metro Pelaw - South Hylton
91	T&W FL200 Light	Simple AT	Furrer+Frey	2017							Tyne & Wear Metro North Tyneside Loop and South Tyneside branch (selected upgrade locations)

No.	Designation	Subtype	Designer	Build Date	Build Voltage	Conversion Date	Conversion Voltage	Conversion Date2	Conversion Voltage3	Country / Administration	Locations
92	N/A	Tramway AT (double CW)	?	2000	750V DC	-	-	-	-	UK / TfL	Croydon - New Addington, Wimbledon, Beckenham Jct & Elmers End
93	N/A	Tramway AT (single CW)		2000							
94	N/A	Tramway FT? AT?	?	1999	750V DC	-	-	-	-	UK	Birmingham Snow Hill - Wolverhampton
95	N/A	Simple AT	Balfour Beatty	1992	750V DC	-	-	-	-	UK	Mancester Victoria - Bury; Cornbrook Junction - G-Mex
96	N/A	MJSA (Mark 3 Simple FT converted from Mark 1)	BICC/Balfour Beatty Conversion	1931	1500V DC	1971	25kV AC	1992	750V DC		Cornbrook Jct - Altrincham
97	N/A	Tramway FT Reduced Tension	Balfour Beatty	1992	750V DC	-	-	-	-		Manchester City Centre (small radius curves)
98	N/A	Tramway FT	Balfour Beatty	1992	750V DC	-	-	-	-		Manchester City Centre
99	N/A	Tramway FT? AT?	?	1994	750V DC	-	-	-	-	UK	Sheffield - Meadowhall, Halfway, Herdings Park, Malin Bridge & Middlewood
100	N/A	Tramway	?	2004	750V DC	-	-	-	-	UK	Nottingham - Phoenix Park & Hucknall
101	N/A	Simple									
102	N/A	Tramway FT?	?	1898	660V DC	-	-	-	-	UK	Blackpool Seafront
103	N/A	Tramway AT	Brecknell Willis	2004	750V DC	-	-	-	-	Ireland	Dublin City Centre
104	N/A	Tramway FT									Dublin Connolly - Tallaght, St.Stephen's Green - Sandyford
105	N/A	Tramway AT	Siemens	2012	750V DC	-	-	-	-	UK	Edinburgh Airport - York Place
106	N/A	Simple AT									
107	Series 2(120) DC conversion	Sagged Simple AT	Network Rail	2017	750V DC	-	-	-	-	UK	Meadowhall South - Rotherham Central

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